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Coupled Into Twelve Large Building  
Structures**

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# **Attenuation of Radio Wave Signals Coupled Into Twelve Large Building Structures**

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## Executive Summary

This is the fourth in a series of NIST Technical Notes (TN) on propagation and detection of radio signals in large building structures (apartment complex, hotel, office building, sports stadium, shopping mall, etc.). The first, second, and third NIST Tech Notes (TN 1540, TN 1541, and TN 1542) described experiments for radio propagation in a structure before, during, and after implosion. The data in these reports give first responders and system designers a better understanding of what to expect from the radio-propagation environment in disaster situations. The goal of this work is to create a large, public-domain data set describing the attenuation of radio signals in various building types in the public safety and cellular telephone bands.

With the above goal in mind, measurements were carried out on 12 different large building structures. Frequencies near public safety and cell phone bands as well as ISM and wireless LAN bands (approximately 50 MHz, 150 MHz, 225 MHz, 450 MHz, 900 MHz, 1.8 GHz, 2.4 GHz, and 4.9 GHz) were chosen for these experiments. We carried out these “radio-mapping” experiments to provide data on how radio signals at the different frequencies coupled into the different building structures. Radio transmitters similar to those used by first responders were used, as well as specially designed transmitters for the higher frequencies. These different transmitters were carried throughout various large building structures, while the received signal was recorded at a fixed receive site located outside the large structures. From this we determined the field-strength variability throughout the structures. Transmitters were also carried around the perimeter of the structures with a fixed receiving site on the outside. The results of these signal-strength measurements and the statistical analysis of the data for these radio-mapping experiments are presented here.

Beside plots of the raw datasets, a series of tables that summarize the processed data by frequency bands are presented in this report. This enables easier comparisons between results from different building or structure types. (Note that the exact frequencies are provided in each of the individual site discussions.) Table entries include a building or structure identifier, the actual frequency tested, the specific reference level used to normalize that particular data set, and then median, mean, and standard deviation results for the normalized data.

Differences in building types make it difficult to make very strong general statements based on the collected data. However, we do observe some general trends in the data. First, examination of the standard deviation yields some interesting insights. In particular, if we exclude the first receiver site for the NIST laboratory in Boulder, we see that the average standard deviation for the six lower frequency bands ranges from 11.8 dB to 13.4 dB. Limited data were collected for the upper two frequencies; but if we include those results, the upper limit of the range increase to 14.9 dB. Across all eight frequency bands, the range of maximum standard deviation covers 16.8 dB to 22.3 dB, with 22.3 dB occurring at 900 MHz. The minimum standard deviation values range from 3.9 dB to 12.1 dB, with 3.9 dB occurring at 1.8 GHz.

Second, in almost all cases, the median value for the power received is less than the average power received. The typical difference is between 2 dB to 3 dB. This suggests that median value may be a better measure for representing the general behavior of the building, or at least a more conservative performance measure.

Third, the histograms (which approximate probability density functions, PDFs) and the empirical cumulative density functions (CDFs) do not appear to follow any typical density function. To some extent, each individual test case will generate a unique density. However, the data do not seem to suggest an obvious average or best approximate density function that could be used as a collective representation of the buildings.

The data presented in this report aid in understanding the issues faced with first responders communicating into and within large building structures. For example, the large amount of attenuation for the signals coupling into the different structures indicates to system designers what a communication link must overcome in order to provide a reliable system. In addition, the measured signal variability indicates the dynamic environment these different buildings present to a communication system.

The results in this report are the fourth in a series of reports detailing experiments performed by NIST in order to provide better understanding of the first responder's radio propagation environment. The first three reports cover implosion experiments that were performed in three different building structures: an apartment building in New Orleans, LA, a large sports stadium (the "Veterans Stadium") in Philadelphia, PA, and a convention center in Washington, DC. Looking ahead, other experiments at different frequencies in other building structures are being performed and will be published separately. We will also be performing measurements to simulate and test the performance of adhoc networks in various building structures; the results of these experiments will also be published separately.





# **Attenuation of Radio Wave Signals Coupled Into Twelve Large Building Structures**

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*In this report, we describe our investigation of radio communication problems faced by emergency responders (firefighters, police, and emergency medical personnel) in disaster situations. A fundamental challenge to communications into and out of large buildings is the strong attenuation of radio signals caused by losses and scattering in the building materials and structure. Besides attenuation, another challenge is the large amount of signal variability that occurs throughout these large structures. We designed experiments in various large building structures in an effort to quantify radio-signal attenuation and variability faced by emergency responders. We carried RF transmitters throughout these structures and placed receiving systems outside the structures. The transmitters were tuned to frequencies near public safety, cell phone bands, and Industrial, Scientific and Medical (ISM) bands, including wireless Local Area Network (LAN) frequencies. This report summarizes the experiments, performed in large building structures. We describe the experiments, detail the measurement system, show primary results of the data collected, and discuss some of the interesting propagation effects we observed.*

*Key words: attenuation; building shielding and coupling; emergency responders; radio communications; radio propagation experiments; signal variability; weak-signal detection*

## **1. Introduction**

When emergency responders enter large structures (e.g., apartment and office buildings, sports stadiums, stores, malls, hotels, convention centers, warehouses, etc.) communication to individuals on the outside is often impaired. Cellular telephones and mobile-radio signal strength is reduced due to (a) attenuation caused by propagation through the building materials, and (b) scattering by the building geometry [1-8]. Also, the large amount of signal variability throughout the structures causes degradation in communication systems.

Here, we report on a National Institute of Standards and Technology (NIST) project to investigate communications problems faced by first responders (firefighters, police and emergency medical personnel) in disaster situations involving large building structures. As part of this effort, we are investigating the propagation and coupling of radio waves into large building structures. This report covers experiments that utilized a single-frequency, unmodulated carrier, whereas a companion report, NIST Technical Note 1546 [9], describes measurements

that support increased understanding of modulated signal transmissions for the public-safety sector.

The experiments reported here were performed in 12 different large building structures and are essentially measurements of the reduction in radio-signal strength caused by propagation through the structures. These structures include four office buildings, two apartment buildings, a hotel, a grocery store, a shopping mall, a convention center, a sports stadium, and an oil refinery. In order to study the radio characteristics of these structures at the various frequencies of interest to first responders, frequencies near public-safety and cell phone bands, as well as ISM and wireless LAN bands (approximately 50 MHz, 150 MHz, 225 MHz, 450 MHz, 900 MHz, 1.8 GHz, 2.4 GHz, 4.9 GHz) were chosen. A detailed description of the transmitters we used is given in detail in Section 3.

The experiments performed here are referred to as “radio mappings.” This involved carrying transmitters (or radios) tuned to various frequencies throughout the 12 structures while recording the received unmodulated signal at a site located outside the building. The reference for these data was a direct, unobstructed, line-of-sight signal-strength measurement with the transmitters external to the different structures and in front of the receiving antennas. The purpose of the radio-mapping measurements was to investigate how the signals at the different frequencies couple into the structures, and to determine the field-strength variability throughout the structures. A detailed description of the measurement system and antennas is given in Section 4.

This report is organized as follows: Section 2 describes the frequencies used in these experiments. Section 3 discusses the transmitters, and Section 4 describes the automated measurement system used in the radio-mapping and propagation measurements. In Section 5, we describe the different structures and detail our experimental procedures for each structure. In Section 6, we present the data collected at various stages of the experiment. Finally, in Section 7, we summarize the results of these experiments and discuss some of the interesting propagation effects observed.

## **2. Frequency Bands**

An overview of the frequencies used by the public-safety community nationwide (federal, state, and local) is given in Table 1, which shows a broad range of frequencies ranging from 30 MHz to 4.9 GHz. The modulation scheme has historically been analog FM, but this is slowly changing to digital as Project 25 radios come online [10]. The modulation bandwidth in the VHF and UHF bands has been 25 kHz, but due to the need for additional communications channels in an already crowded spectrum, most new bandwidth allocations are 12.5 kHz. The older bandwidth allocations will gradually be required to move to narrow bandwidths to increase the user density even further. The crowded spectrum and limited bandwidth are also pushing the move to higher frequency bands in order to support new data-intensive technologies. The cellular phone bands are summarized in Table 2.

As shown in Table 1, frequencies currently used by public safety and other emergency responders and cellular telephones are typically below 2 GHz. New frequency allocations and systems, including higher frequencies (e.g., around 4.9 GHz), will become increasingly important in the future. We chose eight frequency bands below 5 GHz, from about 50 MHz to 4.9 GHz. These include four VHF bands typically used for analog FM voice, one band used for multiple technologies (analog FM voice, digital trunked FM, and cellular telephone), one band near the digital cellular telephone band, and wireless LAN bands.

**Table 1. Public safety community frequencies.**

Frequency band (MHz)	Description
30-50	Used mainly by highway patrols for long-distance propagation; currently being phased out
150-174	Local police and fire. Lower frequency preferred because of its better long-distance propagation quality
406-470	Used by federal officers and others
700-800	Used in urban areas
800-869	Primarily urban usage
4900	A newly allocated band with 50 MHz bandwidth for sending images and broadband data

**Table 2. Cellular Phone Frequencies**

Frequency band (MHz)	Description
800	AMPS or analog systems, migrating to digital trunked and point-to-point communications
1900	PCS or digital system

In designing an experiment to investigate the signal penetration characteristics into large buildings at these different frequency bands, we chose frequencies very close, but not identical, to the above bands. If frequencies were chosen in the public safety or commercial land-mobile bands, interference to the public safety and cellular systems could possibly occur. Conversely, these existing systems could interfere with our experimental setup. In addition, obtaining frequency authorizations in these bands for our experiments would have been problematic due to the intense crowding of the spectrum. To circumvent these issues, we were able to receive temporary authorization to use frequencies in the U.S. Government frequency bands adjacent to these public safety bands. Table 3 lists the frequency bands that were used in the experiments. The lower four bands correspond to the frequencies used by the public-safety community; 902 MHz can be associated with several services including both public safety and cellular phones; the highest frequency is near the digital cellular phone and wireless LAN bands. The exact



frequencies varied depending on which city the experiments were performed. Section 5 describes the different structures and the exact frequencies used in each experiment.

**Table 3. Frequency bands used in the experiments.**

Frequency band (MHz)	Description
49	Simulate a public safety band
162	Simulate a public safety band
226	Simulate a public safety band
448	Simulate a public safety band
902	Simulate a public safety or cellular phone band
1830	Simulate a cellular phone band
2450	Wireless LAN
4900	Recently allocated with 50 MHz bandwidth for sending images and broadband data

### 3. Transmitters

The design requirements for the transmitters used in the experiments discussed here were that they should: (1) transmit an unmodulated carrier at the frequencies listed in the tables above, (2) operate continuously for several hours, and (3) be portable.

To accomplish this, two different types of transmitters were chosen. For the four lower frequency bands (the VHF/UHF public-safety bands), off-the-shelf amateur radios were modified. The modifications included: (1) reprogramming the frequency synthesizer to permit transmitting at government frequencies, (2) disabling the transmitter time-out mode in order to allow for continuous transmission, and (3) connecting a large external battery pack. The specifications of these modified radios then had to be reported to the National Telecommunications and Information Administration (NTIA) frequency coordinator in order to obtain approval for use in government frequency bands. With the larger battery packs, the modified radios could transmit continuously for 12 h to 18 h at an output power of 1 W. The extended transmitting time required us to provide additional cooling since the radios were designed for typical communications, that is, to transmit intermittently with cooling time between transmissions. This was accomplished with cooling fans.

The stability and radiated power from these inexpensive radios was measured over a 24 h period. The modified radios and battery packs were placed in durable orange plastic cases for mobility. The antennas could be mounted either inside or outside the plastic cases. For these measurements, the antennas were mounted on the outside of the cases.

Figure 1 shows the final arrangement of modified transmitters used for the lower four frequency bands. This figure shows one modified transmitter placed in an orange plastic case.

Commercial transmitters were available for the higher frequency bands (900 MHz, 1800 MHz, 2.4 GHz, and 4.9 GHz). These off-the-shelf transmitters were already in plastic protective cases and could transmit continuously for 12 h. Figure 2 shows these transmitters. Note that the cases for the higher-frequency transmitters were not orange, but grey.

#### **4. Receiving Antenna and Measurement System**

The receiving system is sketched in Figure 3. We assembled four antennas on a 4 m mast, as illustrated. The radio-frequency output from each antenna was fed through a 4:1 broadband power combiner. This arrangement gave us a single input to our portable spectrum analyzers, which could then scan over all the frequencies of interest without switching antennas. The four antennas were chosen to be optimal (or at least practical) for each of the frequency bands we were measuring. The selected antennas were an end-fed vertical omnidirectional antenna for 50 MHz, a log-periodic-dipole-array (LPDA) for the 160 MHz, 225 MHz, and 450 MHz bands, and Yagi-Uda arrays for 900 MHz and 1830 MHz. Horn antennas were used for the 2.4 GHz and 4.9 GHz frequency bands. This assembly could then be mounted on a fixed tripod at one of the listening sites, or it could be inserted into a modified garden cart for portable measurements (see Figure 4 and Figure 5). The receiving sites contained, in addition to the antenna system, a generator, uninterruptible power supply (UPS), spectrum analyzer, global positioning system (GPS) receiver, computer, and associated cabling. Photos of the antenna assembly mounted on a tripod and mounted on the mobile cart are shown in Figure 4 and Figure 5.

As shown in Figure 3, the measurement system consists of a portable spectrum analyzer, GPS receiver, and a laptop computer. The data collection process was automated by use of a graphical programming language. This software was designed to control the analyzer, and to collect, process, and save data at the maximum throughput of the equipment. The software controlled the spectrum analyzer via an IEEE-488 interface bus and the GPS receiver via a serial interface. The GPS information was used to record the position of the receiving sites during the measurements.

The software was written to maximize throughput of the data collection process and to run for an undefined time interval. This was achieved by running as parallel processes the collecting, processing, and saving of the data for post-collection processing. The data were continuously read from the spectrum analyzer at its optimal settings and stored in data buffers. These buffers were read and processed for each signal and displayed for operator viewing. The processed data were then stored in additional buffers to be re-sorted and saved to a file on disk.

The initial setup of the parameters for the spectrum analyzer determined the quality of optimization for this process. There were several instrument parameters that were critical during the setup, including the analyzer sweep time, resolution bandwidth, and frequency span of the spectrum analyzer trace. The number and spread of the test frequencies in a particular band influenced the allowed range of adjustment for these parameters. These two factors also influenced the number of traces necessary to cover all the test frequencies. Interference from signals in the adjacent spectrum influenced the instrument setup and data collection speed by forcing smaller resolution bandwidths. The reference level for each trace was also checked and



adjusted during the measurement to improve the resolution and accuracy of the power level reading. All of these factors had some effect on the sampling rate.

The sampling rate of the complete measurement sequence was the major factor in how much spatial resolution we had during walk-through or field-mapping experiments (we also had some flexibility in our walking speed) and the time resolution for recording the signals.

We used three different models of spectrum analyzers, each having a different sampling rate ranging from about 0.5 s to 7 s, to measure all 20 frequencies in the 6 frequency bands. The frequencies were spaced such that we could utilize one spectrum analyzer trace for each band. The reason for the relatively large sampling range is that the first four experiments (New Orleans through the Colorado Springs, CO hotel complex) collected data for all frequencies during a single walk-through. For the remaining eight experiments, only a single frequency was collected during each walk-through, i.e., each frequency required a walk-through. These rates were achieved only after optimizing the instrument control and data transfer processes mentioned above. The data from the spectrum analyzer trace were saved in binary format to disk (to allow us to reprocess the raw data at a later time if needed); they were then processed to extract the signals at each particular frequency. These results were then put into a spreadsheet file and saved with other measurement information. The sampling rates were sufficient for the field-mapping experiments (if we did not walk too fast).

## **5. Building Structure Descriptions and Experimental Set-up**

This section briefly describes the 12 different large building structures used in these experiments and details the experimental set-up. These structures include four office buildings, two apartment buildings, a hotel, a grocery store, a shopping mall, a convention center, a sports stadium, and an oil refinery.

### **5.1 New Orleans, LA Apartment Building**

The building for this set of radio propagation experiments was a 13-story apartment complex located in a suburb of New Orleans, LA (Figure 6), specifically, the William J. Fisher building on Whitney Ave. We performed the radio-mapping measurements prior to the scheduled implosion of the structure. We also performed measurements before, during, and after the implosion of this structure; and details of these implosion measurements are reported in Reference [5].

The 13 stories included a ground-level commons area and parking, and 12 floors with 14 efficiency apartments on each floor. The individual apartments on each level opened to a common outside hallway on the west side of the building. There was an elevator control and maintenance room in a penthouse on the roof of the building. This space was accessed by a metal spiral staircase on the top floor. There were two internal passenger elevators and one external freight elevator near the center of the building. Two external stairwells near each end of the building accessed all floors. There was no basement in this building.

The building was constructed of reinforced concrete, steel, and standard interior finish materials. Significant demolition was already completed when we arrived; all plumbing fixtures, most glass windows and doors, and the contents of the apartments had been removed. The reinforced concrete walls on the lower two levels had been cut away, leaving only support columns remaining. The ground level commons area structure had been demolished and the debris in the area removed. Material had been judiciously removed from certain structural parts of the lower levels, including stairwells and elevator shafts to facilitate a proper collapse during the implosion. Figure 7 shows a few photos of the building interior as it existed during the experiments. The pre-implosion preparation and partial demolition on the lower levels is visible in several of the photos. Figure 8 shows a drawing of the structure.

The purpose of these measurements was to investigate how signals at the different frequencies couple into the building and to determine the field strength variability throughout the building. For the radio-mapping experiments, one fixed receiving site (as described above) was assembled on the northeast side of the building (see Figure 8), approximately 30 m from the northeast corner of the building. During this experiment, the transmitters were carried throughout the building and the received signal levels were recorded. As the received signal was recorded, the location of the transmitters in the buildings was also recorded. The frequencies used in the experiment are shown in Table 4.

**Table 4. Frequencies used in the New Orleans, LA apartment building experiments.**

Frequency band	Description
49.60 MHz	Simulate a public safety band
162.00 MHz	Simulate a public safety band
225.375 MHz	Simulate a public safety band
448.60 MHz	Simulate a public safety band
902.60 MHz	Simulate a public safety or cellular phone band
1832.50 MHz	Simulate a cellular phone band

### 5.2 Philadelphia, PA Sports Stadium

The next structure for the radio propagation experiments was Veterans Stadium, a large sports arena in Philadelphia, PA (see Figure 9). We performed the radio-mapping measurements prior to the scheduled implosion of the structure. We also performed measurements before, during, and after the implosion of this structure, and details of these implosion measurements are reported in Reference [7].

The nearly circular stadium was constructed of reinforced concrete, steel, and standard interior finish materials. Figure 10 show details of the original stadium and some of the preparations and partial demolition of the different sections of the stadium. As shown in these figures, the stadium had multiple levels with large open areas. The exterior perimeter of the stadium was approximately 805 m (1/2 mi). Since this structure was also scheduled for implosion, significant



demolition had already been completed when we arrived; all plumbing fixtures, most glass windows and doors, and other contents had been removed. Material had been judiciously removed from certain structural parts of the lower levels including stairwells and elevator shafts to facilitate a proper collapse during the implosion. Figure 11 shows a plan of the structure and approximate locations of the transmitter and receive instruments.

The purpose of these measurements was to investigate how signals at the different frequencies couple into the stadium and to determine the variability in field strength throughout the stadium. Also, by carrying the transmitters around the exterior perimeter of the stadium the amount of signal blockage caused by the stadium from one side to the other could be investigated. For the radio-mapping experiments, one fixed receiving site (as described above) was assembled on the southwest perimeter of the stadium (see Figure 11), approximately 53 m from Column #10. During this experiment, the transmitters were carried (and at times, driven aboard an all-terrain vehicle or ATV) throughout the stadium and the received signal levels were recorded. Measurements were performed with the receiving antennas polarized in both the horizontal and vertical direction (with respect to the ground). As the received signal was recorded, the location of the transmitters in the buildings was also recorded. The frequencies used in the experiment are shown in Table 5.

**Table 5. Frequencies used in the Philadelphia sports stadium experiments.**

Frequency band (MHz)	Description
49.60	Simulates a public safety band
162.09	Simulates a public safety band
225.30	Simulates a public safety band
448.50	Simulates a public safety band
902.45	Simulates a public safety or cellular phone band
1832.00	Simulates a cellular phone band

### **5.3 Phoenix, AZ Office Building**

The building was an eight-story office building located in Phoenix, AZ at 2375 East Camelback Rd.(Figure 12). There were two sub-basements in the building. The building was constructed of steel with a large number of windows and standard interior-finish materials. The building was fully furnished with office furniture. Measurements were performed during daytime hours. As a result, people were moving throughout the building during the experiments. Figure 13 shows some interior photos of the office building.

For the radio-mapping experiments, one fixed receiving site (as described above) was assembled on the west side of the office building (see Figure 14), approximately 50 m from the front door. During this experiment, the transmitters were carried throughout the building, including the roof and the two sub-basements, and the received signal levels were recorded. Measurements were

performed with the receiving antennas polarized in the vertical direction. As the received signal was recorded, the location of the transmitters in the office buildings was also recorded. The frequencies used in the experiment are shown in Table 6.

**Table 6. Frequencies used in the Phoenix, AZ office building experiments.**

Frequency band (MHz)	Description
154.07	Simulates a public safety band
765	Simulates a public safety band
867	Simulates a cellular phone band

#### 5.4 Colorado Springs, CO, CO Hotel Complex

The building was a 14-story hotel complex located in Colorado Springs, CO, CO (Figure 15). At the time of the measurements, the complex was referred to as the Antlers: Adam's Mark Hotel. The complex had three sub-level parking garages. The complex also had a small conference facility and stores located in the structure. The building was constructed of reinforced concrete and standard interior-finish materials. The building was fully furnished during the experiments. Measurements were performed during daytime hours and, as a result, people were moving throughout the building during the experiments. Figure 16 shows some interior photos of the hotel complex building.

For the radio-mapping experiments, two fixed receiving sites (as described above) were assembled on the outside of the structure (see Figure 17). One was approximately 50 m from the front door, and a similar receiving site was set up in a parking lot near the southwest corner of the building, approximately 30 m from the corner of the building. During this experiment, the transmitters were carried throughout the complex, including the three sub-level parking garages, and the received signal levels were recorded. Measurements were performed with the receiving antennas polarized in both the vertical and horizontal directions. As the received signal was recorded, the location of the transmitters in the hotel was also recorded. The frequencies used in the experiment are shown in Table 7.

**Table 7. Frequencies used in the Colorado Springs, CO, CO hotel complex experiments.**

Frequency band (MHz)	Description
49.60	Simulates a public safety band
162.09	Simulates a public safety band
225.30	Simulates a public safety band
448.50	Simulates a public safety band
902.45	Simulates a public safety or cellular phone band
1830.00	Simulates a cellular phone band

## 5.5 Boulder, CO Grocery Store

The building was a one-story grocery store located in Boulder, CO (Figure 18). This was the King Soopers grocery store located at Table Mesa Dr. and Broadway St. The grocery was constructed of brick and steel. The store was fully furnished during the experiments. Measurements were performed during daytime hours and, as a result, people were moving throughout the store during the experiments. Figure 19 shows some interior photos of the building.

For the radio-mapping experiments, one fixed receiving site (as described above) was assembled on the northwest side of the store building (see Figure 20), approximately 30 m from front door. During this experiment, the transmitters were carried throughout the store as well as around the outside perimeter. Measurements were performed with the receiving antennas polarized in the vertical direction. As the received signals were recorded, the location of the transmitters in the store was also recorded. The frequencies used in the experiment are shown in Table 8.

**Table 8. Frequencies used in the Boulder, CO grocery store experiments.**

Frequency band (MHz)	Description
49.60	Simulates a public safety band
162.09	Simulates a public safety band
225.30	Simulates a public safety band
448.50	Simulates a public safety band
902.75	Simulates a public safety or cellular phone band
1830.00	Simulates a cellular phone band

## 5.6 Gaithersburg, MD Office Building

The building was a ten-story office building at the NIST facility in Gaithersburg, MD (Figure 21). The building was constructed of reinforced concrete. The building was fully furnished during the experiments. Measurements were performed during daytime hours and, as a result, people were moving throughout the structure during the experiments.

For the radio-mapping experiments, one fixed receiving site (as described above) was assembled on the southeast side of the store building (see Figure 22), approximately 60 m from the front door. During this experiment, the transmitters were carried throughout the building. Measurements were performed with the receiving antennas polarized in the vertical direction. As the received signals were recorded, the location of the transmitters in the store was also recorded. The frequencies used in the experiment are shown in Table 9.



**Table 9. Frequencies used in the Gaithersburg, MD office building experiments.**

Frequency band (MHz)	Description
49.60	Simulates a public safety band
162.09	Simulates a public safety band
226.40	Simulates a public safety band
448.30	Simulates a public safety band
902.45	Simulates a public safety or cellular phone band
1830.00	Simulates a cellular phone band

### **5.7 Bethesda, MD Shopping Mall**

The Montgomery Mall was a two-level shopping mall in Bethesda, MD (Figure 23). The building was constructed of reinforced concrete and brick. The building was fully furnished during the experiments. Measurements were performed during daytime hours and, as a result, people were moving throughout the structure during the experiments. Figure 24 shows some internal photos of the mall complex.

For the radio-mapping experiments, two fixed receiving sites (as described above) were assembled on both the east and west sides of the mall (see Figure 25), approximately 60 m from the two entrances. During this experiment, the transmitters were carried throughout the mall. Measurements were performed with the receiving antennas polarized in the vertical polarization. As the received signal was recorded, the location of the transmitters in the store was also recorded. The frequencies used in the experiment are shown in Table 10. This is a two-level facility and during the walk-throughs we stopped at predetermined locations on both the upper and lower levels. An internal floor plan with these locations is shown in Figure 26. The green arrows in the figure represent the actual paths that were walked.

**Table 10. Frequencies used in the Bethesda, MD shopping mall experiments.**

Frequency band (MHz)	Description
49.60	Simulates a public safety band
162.09	Simulates a public safety band
226.40	Simulates a public safety band
448.30	Simulates a public safety band
902.45	Simulates a public safety or cellular phone band
1830.00	Simulates a cellular phone band

## 5.8 Silver Spring, MD Office Building

The building was the 11-story Discovery office building in Silver Spring, MD (Figure 27). The building was constructed of concrete, steel, and glass. The building included a three-level underground parking garage. The building had been recently built and most rooms were furnished with cubicle dividers and typical office furniture, while some were essentially empty. As in earlier measurements, there were people moving about in the structure during the tests in the occupied sections of the building. Figure 28 shows some internal photos of the office building. This structure consisted of two adjoining units or buildings. While walking through the building, we stopped at the various locations on each floor and as well as at the corridor adjoining the two buildings. Each stop is labeled with letters A-I in Figure 29 and on the curves in the next section.

For the radio-mapping experiments, one fixed receiving site (as described above) was assembled on the east side of the building (see Figure 30), approximately 20 m from the main entrance. During this experiment, the transmitters were carried throughout the building, including the three-level underground parking garage. Measurements were performed with the receiving antennas polarized in the vertical direction. As the received signals were recorded, the location of the transmitters in the store was also recorded. The frequencies used in the experiment are shown in Table 11.

**Table 11. Frequencies used in the Silver Spring, MD Discovery office building experiments.**

Frequency band (MHz)	Description
49.60	Simulates a public safety band
162.09	Simulates a public safety band
226.40	Simulates a public safety band
448.30	Simulates a public safety band
902.45	Simulates a public safety or cellular phone band
1830.00	Simulates a cellular phone band

## 5.9 Washington, DC Convention Center

The structure in the experiment was the old Washington, DC Convention Center (see Figure 31). We performed these radio-mapping measurements prior to the scheduled implosion of the structure. We also performed measurements before, during, and after the implosion of this structure, and details of these implosion measurements are reported in Reference [8].

This massive two-level structure was constructed of reinforced concrete, steel, and standard interior finish materials. Figure 32 shows some internal photos of the convention center. As shown in Figure 31, the convention center had two large levels with three levels of offices. This

structure was scheduled for demolition and significant demolition had already been completed when we arrived; all plumbing fixtures, most glass windows and doors, and other contents had been removed.

Figure 33 shows the locations of the three receive sites for the experiments. These three fixed receiving sites were assembled on the perimeter of the convention center. Receiving site RX 1 was placed approximately 23 m (75 ft) from the northwest perimeter of the convention center. Receiving site RX 2 was placed approximately 23 m (75 ft) from the northeast perimeter of the convention center. Receiving site RX 3 was placed approximately 15 m (50 ft) from the southeast perimeter of the convention center. During these experiments, the transmitters were carried throughout the convention center, and the received signal levels were recorded. Measurements were performed with the receiving antennas polarized in the vertical direction (with respect to the ground). As the received signals were recorded, the locations of the transmitters in the convention center were also recorded. The frequencies used in the experiment are shown in Table 12.

**Table 12. Frequencies used in the Washington DC convention center experiments.**

Frequency band (MHz)	Description
49.60	Simulates a public safety band
162.09	Simulates a public safety band
226.40	Simulates a public safety band
448.30	Simulates a public safety band
902.45	Simulates a public safety or cellular phone band
1830.00	Simulates a cellular phone band

### 5.10 Boulder, CO Apartment Building

The building was the 11-story Horizon West apartment building in Boulder, CO (Figure 34). The building was constructed of reinforced concrete, steel, and brick with standard interior-finish materials. The building was fully furnished and occupied during the experiments. Measurements were performed during daytime hours and, as a result, people were moving throughout the building during the experiments. Figure 35 and Figure 36 show the two receiver setups at Horizon West, while Figure 37 displays internal photos of the apartment building.

For the radio-mapping experiments, two fixed receiving sites (see Figure 35) were assembled on the east side and north side of the apartment building, approximately 60 m and 80 m from the apartment building. During these experiments, the transmitters were carried throughout the building. Measurements were performed with the receiving antennas polarized in the vertical direction. As the received signal was recorded, the location of the transmitters in the apartment building was also recorded. The frequencies used in the experiment are shown in Table 13.



**Table 13. Frequencies used in the Boulder, CO apartment building experiments**

Frequency band (MHz)	Description
162.075	Simulates a public safety band
230.0	Simulates a public safety band
439.25	Simulates a public safety band
908.0	Simulates a public safety or cellular phone band
1830.0	Simulates a cellular phone band
2445.0	Simulates a wireless LAN
4900.0	Simulates a public safety band

### **5.11 Commerce City, CO Oil Refinery**

The facility was the SUNCOR Energy oil refinery in Commerce City, CO (Figure 38). The refinery was basically an outdoor facility with several intricate piping systems. Measurements were performed during daytime hours and, as a result, people were moving throughout the refinery. During these experiments, the transmitters were carried throughout the refinery. There were two paths chosen for these tests, one through the center of the processing section with dense piping, and the other around the cluster of large metal storage tanks. During the measurements, the transmitters were carried throughout the dense piping system and driven around the large storage tanks. Figure 39 and Figure 40 show some photos of the refinery complex in which the transmitters were carried, while Figure 41 shows the driven section of the refinery during the data collection process.

For the radio-mapping experiments, two fixed receiving sites (as described above) were assembled on the south side and north side of the refinery complex (see Figure 42), approximately 100 m and 30 m from the piping structures. The green arrows in the figure represent the actual paths that were walked. Measurements were performed with the receiving antennas polarized in the vertical direction. As the received signals were recorded, the location of the transmitters in the refinery complex was also recorded. The frequencies used in the experiment are shown in Table 14.

**Table 14. Frequencies used in the Commerce City, CO oil refinery complex experiments.**

Frequency band (MHz)	Description
49.85	Simulates a public safety band
162.075	Simulates a public safety band
230.0	Simulates a public safety band
439.25	Simulates a public safety band
908.0	Simulates a public safety or cellular phone band
1830.1	Simulates a cellular phone band
2445.0	Simulates a wireless LAN
4900.0	Simulates a public safety band

### **5.12 NIST Boulder, CO Laboratory**

This building was the main building (referred to as the Radio Building) at the NIST laboratories in Boulder, CO (see Figure 43). The building is constructed of reinforced concrete and is basically a four-story building. However, the building is built on a hillside, and consequently, some locations in the building are below ground level. Measurements were performed during daytime hours and, as a result, people were moving throughout the building during the experiments.

For the radio-mapping experiments, two fixed receiving sites (as described above) were assembled on the south side of the laboratory building (see Figure 44 and Figure 45). The receive site at Wing 4 was located on the landing dock, while the receive site at Wing 6 was approximately 10 m from the building. During these experiments, the transmitters were carried throughout the laboratory. Measurements were performed with the receiving antennas polarized in the vertical direction. As the received signals were recorded, the location of the transmitters in the buildings was also recorded. The frequencies used in the experiment are shown in Table 15.

**Table 15. Frequencies used in the NIST Boulder laboratory experiments.**

Frequency band (MHz)	Description
49.8	Simulates a public safety band
162.075	Simulates a public safety band
230.0	Simulates a public safety band
439.25	Simulates a public safety band
908.0	Simulates a public safety or cellular phone band
1830.0	Simulates a cellular phone band
2445.0	Simulates a wireless LAN
4900.0	Simulates a public safety band

## **6. Experimental Results**

In this section the measured data are presented from several perspectives. The section is divided into subsections, with each subsection discussing a different set of building structure measurements. Plots of the walk-through data, normalized to a reference point, are provided for the investigated frequencies, and the appropriate figure numbers are indicated in the subsection discussions. Plots of the walk-through data statistics are also included. General descriptions of the experimental setups for the various sites were provided earlier in Sections 4 and 5. Any unique features of a site that appear to impact the collected data are pointed out in the appropriate results subsection. The common acronyms and abbreviations used in the labeling of the walk-through figures and statistical plots are provided in Table 16.

**Table 16. Common abbreviations used in the statistic tables and data igures**

<i>Acronym or Abbreviation</i>	<i>Meaning</i>
Apmt.	Apartment
Approx.	Approximate
Col.	Column
Fl., FL, fl.	Floor
Freq.	Frequency
Horiz.	Horizontal
LOS	line-of-site
Lx	Level $x$ or floor $x$ , where $x$ is a number
N	North
N.E.	Northeast
N.W.	Northwest
Ref.	Reference signal level
Polar.	Polarization
S	South
Std. dev.	Standard deviation
S.E.	Southeast
S.W.	Southwest
Vert.	Vertical

The collected data are plotted as a power level versus the sample number, where the sample number corresponds to different locations in the building structure. The power level is normalized to a reference signal, which is collected at a location with line-of-sight to the receiver. Note that the reference level was not always the strongest measured signal level. Also, in a few cases, a line-sight-sight reference was not available, and an average of near-maximum values was utilized as the reference value instead. This difference in reference level does not affect the variability of the signal level, but does impact the median and the mean. The histograms are created by use of a bin width of 1 dB, and are based on normalized received signal power levels. Median, mean, and standard deviation statistics are also calculated based on the normalized decibel values of the measured data.

We will present the data collected for each building in the chronological order in which it was collected. The data are presented in two forms. First, we present the received power levels versus location in the particular building structure. Second, we present the data in a statistical manner using histograms and cumulative density functions (CDFs). After we have presented all the data for each building, the next section summarizes the data from all 12 buildings as a whole, and we draw a few conclusions.



## 6.1 New Orleans, LA Apartment Building Results

The apartment building in New Orleans, LA provided the first set of data collected (in chronological order). Plots of the signal power versus sample number are provided for the six lower-frequency bands in Figure 46 to Figure 51. Corresponding histograms and empirical cumulative density functions (CDFs) are found in Figure 52 and Figure 53. In these experiments, approximately 500 samples were collected for each frequency over the complete building walk-through, and the time between samples was approximately 6 s. The reference level for the six frequencies is much higher than that used in most subsequent experiments, which suggests a starting location quite close to the receiver site. As we will see, the standard deviation results are quite similar to results from the other buildings. Also, this particular building had been prepared for demolition, and thus did not contain material such as window glass. This removal of substantial portions of building material, as well as internal content, may have impacted the data. We also performed measurements before, during, and after the implosion of this structure and details of these implosion measurements are reported in Reference [5].

## 6.2 Philadelphia, PA Sports Stadium Results

A large sports stadium was the second structure investigated. The data collected consisted of a walk-through within the stadium and around the exterior of the stadium for both horizontal and vertical antenna polarizations at the receiver. A sampling rate of approximately 6 s per frequency resulted in small numbers of samples corresponding to a large geographic area or path length. The limited number of sample points over a long path distance does not provide a high resolution of the signal power behavior. Also, the data shown are normalized to a 0 dBm reference level (all other results do not utilize a normalized reference level). The data for both the interior and exterior of the stadium are given in Figures 54 through 92.

The walk-through plots for the interior of the stadium are found in Figure 54 to Figure 59 (horizontal polarization), Figure 62 to Figure 67 (horizontal polarization), and Figure 70 to Figure 75 (vertical polarization). Statistical plots corresponding to these three sets of figures are found in Figure 60 and Figure 61, Figure 68 and Figure 69, and Figure 76 and Figure 77. Note that the two inside walk-throughs with horizontal polarization do not directly concatenate, but in general, the combination of the two walk-throughs covers the same path as the single vertical polarization inside walk-through.

Stadium exterior walk-through plots are found in Figure 78 to Figure 83 (horizontal polarization), and Figure 86 to Figure 91 (vertical polarization). The corresponding statistical plots are shown in Figure 84 and Figure 85 and Figure 92 and 93, respectively.

The most noticeable difference between the five cases is that for all frequencies above 50 MHz, the median of the outside walk with the vertical polarization is at least 3.9 dB worse than the four other walks. The standard deviation is also greater than 18.4 dB for all frequencies for the vertical polarization outside walk. We also performed measurements before, during, and after the implosion of this structure, and details of these implosion measurements are reported in Reference [7].

### 6.3 Phoenix, AZ Office Building Results

Three frequencies were measured at the Phoenix office building experiments described in Section 5.3. Walk-through plots are provided in Figure 94 through Figure 96, and the corresponding statistical plots are shown in Figure 97. As noted on the walk-through plots, a line-of-sight to the receiver location was possible only for the 154 MHz case. However, this did not appear to significantly alter the overall statistics in Figure 97, which depicts both a higher reference value and a larger standard deviation for the 154 MHz case, as compared to either the 765 or 867 MHz cases.

### 6.4 Colorado Springs, CO, CO Hotel Complex Results

The Colorado Springs, CO measurements consisted of a walk-through with a vertically polarized receive antenna, and a walk-through with a horizontally polarized receive antenna. Data were collected at two different receive locations as described in Section 5.4. Six frequencies were measured at the Colorado Springs, CO hotel, and the data is presented in Figures 98 through 129. The highest frequency, 1830 MHz, did not provide meaningful statistics, as is evident by the walk-through plots in Figure 103, Figure 111, Figure 119, and Figure 127. Hence, no statistics are provided for the 1830 MHz case. Note that this indicates that at 1830 MHz, the building essentially attenuated the transmitted signal below the detection threshold of the spectrum analyzer.

Figure 98 through Figure 103 show the walk-through results for a vertically polarized receiver at site 1, with the corresponding statistics for the five lowest frequencies displayed in Figure 104 and Figure 105. Frequencies of 162 MHz, 225 MHz, 449 MHz, and 902 MHz behave quite similarly, as is evident by both the walk-through and statistics figures. However, the 49 MHz case demonstrates an increase in the reference signal level of greater than 16 dB compared to those four frequencies.

The site 1 horizontally polarized receive antenna results in Figure 106s through Figure 111, with corresponding statistics in Figure 112 and Figure 113, show some differences when compared to the site 1 vertically polarized receiver results. The basic shape of the histogram now illustrates a normal distribution (instead of an exponential), and the standard deviation decreases by at least 6.5 dB for all five frequencies.

The walk-through results at receive site 2 with a vertically polarized receive antenna for the six frequencies are shown in Figure 114 to Figure 119, with the corresponding statistics shown in Figure 120 and Figure 121. In comparison to the case for site 1, the most noticeable difference is a decrease of at least 7.5 dB in the standard deviation across all five frequencies. The shapes of the histograms approximate exponential distributions, which is consistent with the site 1 results.

Figure 122 through Figure 127 show the results for a horizontally polarized receive antenna at site 2, with corresponding statistics results displayed in Figure 128 and Figure 129. In comparison with the results for site 1, the shapes of the histograms, except for the 49 MHz case,



are tending toward a normal distribution. Interestingly, the standard deviations for all five frequencies are within 1.1 dB for this polarization at site 2, which represents the smallest spread in standard deviation for all four polarization and locations combinations.

## **6.5 Boulder, CO Grocery Store Results**

The walk-through results for six frequencies tested in the Boulder grocery store are provided in Figure 130 through Figure 135. Due to the openness of both the entrance and the floor space of the building, the walk-through plots depict a clear geometrical distance dependency between the transmitter and the receiver for all frequencies. For example, see the section in the figures where the transmitter was carried back and forth along the aisles. The histogram shapes appear to follow a normal distribution, and the data exhibit similar statistical values for all frequencies (see Figure 136 and Figure 137). The openness of the facility is most likely responsible for this fairly close agreement across all frequencies.

## **6.6 Gaithersburg, MD Office Building Results**

Figure 138 through Figure 143 depict the walk-through data for the office building in Gaithersburg, MD. The corresponding statistics are shown in Figure 144 and Figure 145. An interesting observation is that while all the walk-through results show the same general trends, the case of 1830 MHz clearly shows the received signal falling into the noise region when the transmitter is in the basement. Also, the shape of the histograms for 226 and 448 MHz does not mimic those for the other four frequencies, which have a significant number of samples that are either near or below the noise floor.

## **6.7 Bethesda, MD Shopping Mall Results**

The both the walk-through data and the statistics data are presented in Figures 146 through 161. Walk-through data for receive sites 1 and 2 are plotted in

Figure 146 through Figure 151, and Figure 154 through Figure 159, respectively. The corresponding statistics plots for site 1 are shown in Figure 152 and Figure 153, while the statistics for site 2 are shown in Figure 160 and Figure 161. The results for site 1 are quite similar across all six frequencies, with the most noticeable difference occurring at 1830 MHz. At this frequency, the received signal is either below or near the noise floor for many of the samples. This shows up in the sharp rise in the CDF at approximately -34 dB for the 1830 MHz plot in Figure 151. The first five frequencies do not exhibit this step-function-like behavior.

At the second receiver site, the walk-through data again show very similar general behavior, such as the clear peaks when there is a line-of-sight at the Sears location. Also, the same step-function-like behavior shows up in the CDF of the 1830 MHz results.

## **6.8 Silver Springs, MD Office Building Results**

Figure 162 to Figure 167 show the walk-through data for the Silver Springs office building. The number/letter pairs refer to a floor and location, see Figure 29. Note that the transmitters were carried into the lobby, transported by the elevator to the ninth floor, carried through several floors, into the basement, and then finally back to the lobby. The corresponding statistics plots are presented in Figure 168 and Figure 169.

As in the shopping mall discussed above, the CDF of the 1830 MHz case resembles a step function. The standard deviation is approximately half the value compared to the other frequencies, as well.

## **6.9 Washington, DC Convention Center Results**

Three receiver sites collected data at the Washington, DC convention center. The both the walk-through data and the statistics data for all three sites are presented in Figures 170 through 193. The corresponding walk-through data results for receiver sites labeled 1, 2, and 3 are provided in Figure 170 through Figure 175, Figure 178 through Figure 183, and Figure 186 through Figure 191, respectively. The statistics plots for receiver sites 1, 2, and 3 are found in Figure 176 and Figure 177, Figure 184 and Figure 185, and Figure 192 and Figure 193, respectively.

The walk-through data plots depict very similar behavior for all frequencies at the three receiving sites. At 162 MHz, the standard deviation spread between sites is 3.2 dB, which is the maximum spread. It is interesting to note that the 1.8 GHz band demonstrates the lowest average standard deviation (approximately 11.8 dB), which is consistent with the rapid rise on the slope of the empirical CDFs. We also performed measurements before, during, and after the implosion of this structure, and details of these implosion measurements are reported in Reference [8].

## **6.10 Boulder, CO Apartment Building Results**

Two receive sites were used to collected data at the Boulder apartment building. The walk-through results for site 1 are shown in Figure 194 through 200, with the statistics plots provided in Figure 201 through 203. Site 2 results are shown in Figure 204 through 210, with the corresponding statistics plotted in Figure 211 through 213.

## **6.11 Commerce City, CO Oil Refinery Results**

The oil refinery results from a walk-through of the plant come from two receive sites, north and south. The both the walk-through data and the statistics data for both receive sites are presented in Figures 214 through 235. Figure 214 through Figure 221 represent the south site data while Figure 225 through Figure 232 show the north site data. The corresponding statistics data plots are Figure 222 to Figure 224, and Figure 233 to Figure 235, respectively.

Comparison between the collected data for the walk-through reveals that the median and mean for south site are in general lower than for the north site. The standard deviations are quite similar; the greatest difference (3.4 dB) occurs at 50 MHz. Examination of the individual walk-through data plot shows that position 4 creates the strongest signal at the south receive site. The top of the tower location presents a much stronger relative signal at the north site than at the south site.

Data at the oil refinery were also collected along a road located among the large storage tanks. The collected data at the north site only are shown in Figure 236 through Figure 243, with the corresponding statistics plots provided in Figure 244 to Figure 246.

## **6.12 NIST Boulder, CO Laboratory Results**

Building 1 (or the Radio Building) at the NIST laboratory in Boulder, CO represents the final data collection site. One receiver site was located at the end of Wing 4 of the building (site 1), but still within the building structure. The second receiver location (site 2) was located outside off of Wing 6. Note that the data for site 1 contain only the walk-throughs to point D, or the farthest point, but not the return walk-through data. The both the walk-through data and the statistics data for both receive sites are presented in Figures 247 through 268.

Figure 247 through Figure 254 and Figure 258 through Figure 265 show the walk-through plots for receiver sites 1 and 2, respectively. The corresponding statistics plots are provided in Figure 255 and Figure 257, and Figure 266 and Figure 268, respectively.

The most significant difference between the two results shows up in the standard deviation. Across all frequencies, results for site 1 indicate a deviation at least 7.4 dB greater than results for site 2. This discrepancy is possible due to the close proximity of the path taken to receive site 1 during the walk-through, which created a much larger dynamic range for receive site 1 than for site 2. The discrepancy can also be due to the tunnel effect for the receiver inside the building, while the outside site had standard building penetration rather than waveguide below cutoff behavior.

## **7. Summary of Results and Conclusions**

The following tables, Tables 17 through 28, present summaries of the processed data by frequency bands. This enables easier comparisons between results from different building or structure types. (Note that the exact frequencies are provided in each of the individual site discussions.) Table entries include a building or structure identifier, the actual frequency tested, the specific reference level used to normalize that particular data set, and then median, mean, and standard deviation results for the normalized data.



**Table 17. 50 MHz frequency band.**

Structure/Location	Freq. (MHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>New Orleans, LA apartment</b>	50	-3.7	-35.9	-37.5	13.1
<b>Philadelphia, PA sports stadium</b>					
First inside walk; horiz. polar.	50	0.0	-34.0	-29.5	15.5
Second inside walk; horiz. polar.	50	0.0	-44.4	-42.8	8.8
Inside walk; vert. polar.	50	0.0	-36.8	-32.8	14.2
Outside walk; horiz. polar.	50	0.0	-32.8	-27.8	15.5
Outside walk; vert. polar.	50	0.0	-41.8	-36.0	18.4
<b>Phoenix, AZ office</b>					
<b>Colorado Springs, CO, CO hotel complex</b>					
First walk-through, Receive site 1	50	-23.7	-62.8	-58.0	17.6
Second walk-through, Receive site 1	50	-29.2	-58.2	-56.2	11.1
First walk-through, Receive site 2	50	-57.6	-14.9	-12.3	5.3
Second walk-through, Receive site 2	50	-31.5	-62.9	-57.8	12.4
<b>Grocery Store (Boulder, CO)</b>	50	-35.4	-45.1	-43.1	12.0
<b>NIST office (Gaithersburg, MD)</b>	50	-21.3	-68.6	-62.1	16.5
<b>Shopping mall (Bethesda, MD)</b>					
Receiver site 1	50	-47.3	-49.4	-47.2	5.9
Receiver site 2	50	-48.9	-44.4	-42.2	9.7
<b>Discovery office (Silver Spring, MD)</b>	50	-21.6	-64.2	-63.7	11.4
<b>Washington, DC convention center</b>					
Receiver site 1	50	-19.1	-63.9	-62.3	12.5
Receiver site 2	50	-26.3	-50.6	-49.8	14.4
Receiver site 3	50	-13.3	-67.4	-65.3	15.5
<b>Horizon West Apartment (Boulder)</b>					
Receiver site 1					
Receiver site 2					
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	50	-30.2	-57.1	-55.9	13.2
Walk-through, north receive site	50	-25.6	-52.6	-50.3	16.6
Road drive, north receive site	50	-27.5	-51.9	-51.2	7.3
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	50	-29.6	-64.4	-50.2	24.3
Receiver site 2	50	-54.1	-40.1	-35.0	11.9

Table 18. 150 MHz frequency band.

Structure/Location	Freq. (MHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>New Orleans, LA apartment</b>	162	-2.5	-28.2	-27.9	11.8
<b>Philadelphia, PA sports stadium</b>					
First inside walk; horiz. polar.	162	0.0	-37.4	-34.2	15.0
Second inside walk; horiz. polar.	162	0.0	-34.3	-35.6	10.6
Inside walk; vert. polar.	162	0.0	-42.5	-39.2	15.8
Outside walk; horiz. polar.	162	0.0	-32.1	-28.9	14.8
Outside walk; vert. polar.	162	0.0	-53.2	-47.7	19.2
<b>Phoenix, AZ office</b>	154	-12.8	-62.3	-60.9	18.4
<b>Colorado Springs, CO Hotel Complex</b>					
First walk-through, Receive site 1	162	-43.9	-39.5	-37.6	15.5
Second walk-through, Receive site 1	162	-40.5	-41.4	-41.7	8.7
First walk-through, Receive site 2	162	-52.0	-17.5	-15.4	7.8
Second walk-through, Receive site 2	162	-32.8	-48.2	-46.6	11.8
<b>Grocery store (Boulder, CO)</b>	162	-36.5	-38.6	-36.0	11.8
<b>NIST office (Gaithersburg, MD)</b>	162	-41.9	-42.8	-41.6	12.5
<b>Shopping mall (Bethesda, MD)</b>					
Receiver site 1	162	-48.7	-48.6	-46.5	5.8
Receiver site 2	162	-55.2	-38.0	-35.8	8.1
<b>Discovery office (Silver Spring, MD)</b>	162	-30.9	-57.9	-55.7	10.3
<b>Washington, DC convention center</b>					
Receiver site 1	162	-26.3	-61.9	-59.9	12.1
Receiver site 2	162	-21.3	-65.0	-61.1	15.3
Receiver site 3	162	-16.9	-68.9	-66.0	14.4
<b>Horizon West apartment (Boulder, CO)</b>					
Receiver site 1	162	-17.0	-25.9	-24.9	10.4
Receiver site 2	162	-24.4	-27.8	-27.4	10.1
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	162	-20.4	-51.2	-47.9	13.8
Walk-through, north receive site	162	-25.0	-35.5	-33.7	13.9
Road drive, north receive site	162	-25.7	-48.3	-44.8	13.7
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	162	-12.5	-73.1	-54.8	33.7
Receiver site 2	162	-41.0	-59.9	-50.8	14.6



Table 19. 225 MHz frequency band.

Structure/Location	Freq. (MHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>New Orleans, LA apartment</b>	225	-9.3	-34.5	-33.1	11.2
<b>Philadelphia, PA sports stadium</b>					
First inside walk; horiz. polar.	225	0.0	-34.4	-29.1	14.4
Second inside walk; horiz. polar.	225	0.0	-37.6	-38.9	9.6
Inside walk; vert. polar.	225	0.0	-36.3	-34.2	13.5
Outside walk; horiz. polar.	225	0.0	-38.0	-34.0	18.3
Outside walk; vert. polar.	225	0.0	-53.3	-49.5	20.3
<b>Phoenix, AZ office</b>					
<b>Colorado Springs, CO, CO hotel complex</b>					
First walk-through, Receive site 1	225	-40.0	-42.0	-39.5	16.1
Second walk-through, Receive site 1	225	-43.7	-36.3	-36.8	9.1
First walk-through, Receive site 2	225	-50.9	-19.3	-16.8	7.6
Second walk-through, Receive site 2	225	-37.0	-46.8	-44.9	11.4
<b>Grocery store (Boulder, CO)</b>	225	-32.6	-45.8	-43.0	14.5
<b>NIST office (Gaithersburg, MD)</b>	226	-30.6	-44.7	-44.1	14.7
<b>Shopping mall (Bethesda, MD)</b>					
Receiver site 1	226	-41.7	-51.6	-49.9	7.1
Receiver site 2	226	-45.6	-41.7	-39.8	11.1
<b>Discovery office (Silver Spring, MD)</b>	226	-21.7	-61.3	-60.3	11.1
<b>Washington, DC convention center</b>					
Receiver site 1	226	-9.1	-65.3	-64.1	13.3
Receiver site 2	226	-15.8	-58.8	-56.8	14.6
Receiver site 3	226	-7.5	-64.2	-62.3	15.4
<b>Horizon West apartment (Boulder, CO)</b>					
Receiver site 1	230	-12.9	-26.8	-25.9	10.4
Receiver site 2	230	-29.2	-19.3	-19.0	9.5
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	230	-17.7	-49.0	-47.3	14.9
Walk-through, north receive site	230	-23.2	-34.8	-34.1	14.5
Road drive, north receive site	230	-25.8	-47.5	-50.1	5.9
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	230	-35.0	-52.6	-43.3	28.7
Receiver site 2	230	-44.0	-50.7	-44.2	16.7

**Table 20. 450 MHz frequency band.**

Structure/Location	Freq. (MHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>New Orleans, LA apartment</b>	449	-3.2	-42.6	-39.7	10.3
<b>Philadelphia, PA sports stadium</b>					
First inside walk; horiz. polar.	449	0.0	-35.9	-32.4	15.1
Second inside walk; horiz. polar.	449	0.0	-35.7	-35.9	8.9
Inside walk; vert. polar.	449	0.0	-29.8	-28.7	11.3
Outside walk; horiz. polar.	448	0.0	-37.9	-32.5	16.0
Outside walk; vert. polar.	448	0.0	-53.8	-44.8	20.7
<b>Phoenix, AZ office</b>					
<b>Colorado Springs, CO, CO hotel complex</b>					
First walk-through, Receive site 1	449	-45.1	-31.9	-30.0	17.6
Second walk-through, Receive site 1	449	-34.0	-37.8	-39.1	10.3
First walk-through, Receive site 2	449	-46.3	-22.7	-20.3	8.4
Second walk-through, Receive site 2	449	-42.9	-38.7	-36.3	12.1
<b>Grocery store (Boulder, CO)</b>	449	-34.6	-30.7	-29.2	11.7
<b>NIST office (Gaithersburg, MD)</b>	448	-30.1	-46.7	-46.9	14.1
<b>Shopping mall (Bethesda, MD)</b>					
Receiver site 1	448	-41.8	-54.7	-52.8	5.6
Receiver site 2	448	-52.4	-39.9	-35.7	12.2
<b>Discovery office (Silver Spring, MD)</b>	448	-29.6	-52.6	-52.4	11.2
<b>Washington, DC convention center</b>					
Receiver site 1	448	-18.6	-56.2	-54.7	14.0
Receiver site 2	448	-18.2	-58.1	-56.9	13.4
Receiver site 3	448	-14.3	-58.9	-57.3	15.1
<b>Horizon West apartment (Boulder, CO)</b>					
Receiver site 1	439	-13.6	-27.2	-25.4	11.0
Receiver site 2	439	-33.3	-17.9	-18.7	9.6
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	439	-23.8	-47.6	-45.3	14.6
Walk-through, north receive site	439	-23.9	-38.5	-37.8	14.6
Road drive, north receive site	439	-26.6	-48.4	-45.3	13.6
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	439	-36.5	-48.4	-37.9	28.2
Receiver site 2	439	-60.0	-37.1	-30.7	13.9

**Table 21. 900 MHz frequency band.**

Structure/Location	Freq. (MHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>New Orleans, LA apartment</b>	903	-1.0	-34.8	-34.2	13.8
<b>Philadelphia, PA sports stadium</b>					
First inside walk; horiz. polar.	902	0.0	-40.7	-35.8	15.3
Second inside walk; horiz. polar.	902	0.0	-49.8	-50.2	15.8
Inside walk; vert. polar.	902	0.0	-27.5	-27.2	11.3
Outside walk; horiz. polar.	902	0.0	-44.2	-37.2	17.0
Outside walk; vert. polar.	902	0.0	-53.9	-46.6	22.3
<b>Phoenix, AZ office</b>	867	-34.4	-38.3	-37.9	13.5
<b>Colorado Springs, CO, CO hotel complex</b>					
First walk-through, Receive site 1	902	-42.2	-37.8	-34.1	18.8
Second walk-through, Receive site 1	902	-34.3	-42.7	-42.8	10.4
First walk-through, Receive site 2	902	-49.1	-21.1	-20.3	8.4
Second walk-through, Receive site 2	902	-41.3	-44.9	-42.2	11.3
<b>Grocery store (Boulder, CO)</b>	903	-27.9	-35.3	-33.8	12.3
<b>NIST office (Gaithersburg, MD)</b>	902	-21.8	-59.7	-57.7	14.1
<b>Shopping mall (Bethesda, MD)</b>					
Receiver site 1	902	-49.0	-47.2	-44.6	6.3
Receiver site 2	902	-41.1	-54.5	-50.4	11.2
<b>Discovery office (Silver Spring, MD)</b>	902	-16.0	-72.1	-70.4	10.5
<b>Washington, DC convention center</b>					
Receiver site 1	902	-16.5	-63.8	-61.8	14.5
Receiver site 2	902	-23.5	-55.4	-54.0	13.7
Receiver site 3	902	-9.4	-68.5	-66.4	14.1
<b>Horizon West apartment (Boulder, CO)</b>					
Receiver site 1	908	-23.1	-27.8	-27.0	10.9
Receiver site 2	908	-39.4	-21.2	-21.4	9.5
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	908	-31.6	-47.2	-44.8	14.8
Walk-through, north receive site	908	-25.7	-44.8	-42.7	17.0
Road drive, north receive site	908	-30.0	-51.0	-45.6	13.6
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	908	-39.1	-32.4	-28.9	25.1
Receiver site 2	908	-45.4	-50.1	-44.1	15.6



Table 22. 1.8 GHz frequency band.

Structure/Location	Freq. (GHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>New Orleans, LA apartment</b>	1.83	-15.8	-37.0	-34.0	13.1
<b>Philadelphia, PA sports stadium</b>					
First inside walk; horiz. polar.	1.83	0.0	-44.9	-40.4	14.3
Second inside walk; horiz. polar.	1.83	0.0	-22.0	-20.9	8.4
Inside walk; vert. polar.	1.83	0.0	-26.9	-26.5	9.5
Outside walk; horiz. polar.	1.83	0.0	-45.6	-39.4	17.1
Outside walk; vert. polar.	1.83	0.0	-49.5	-42.8	19.6
<b>Phoenix, AZ office</b>					
<b>Colorado Springs, CO, CO hotel complex</b>					
First walk-through, Receive site 1					
Second walk-through, Receive site 1					
First walk-through, Receive site 2					
Second walk-through, Receive site 2					
<b>Grocery store (Boulder, CO)</b>	1.83	-34.2	-40.8	-39.3	12.0
<b>NIST office (Gaithersburg, MD)</b>	1.83	-30.6	-59.9	-55.6	12.2
<b>Shopping mall (Bethesda, MD)</b>					
Receiver site 1	1.83	-62.2	-34.1	-33.3	3.9
Receiver site 2	1.83	-55.0	-41.0	-37.7	8.5
<b>Discovery office (Silver Spring, MD)</b>	1.83	-25.9	-69.5	-67.2	5.7
<b>Washington, DC convention center</b>					
Receiver site 1	1.83	-27.5	-60.8	-57.9	11.4
Receiver site 2	1.83	-25.5	-60.1	-58.0	11.8
Receiver site 3	1.83	-24.6	-60.7	-58.2	12.1
<b>Horizon West apartment (Boulder, CO)</b>					
Receiver site 1	1.83	-32.4	-26.2	-25.6	12.8
Receiver site 2	1.83	-44.0	-25.6	-25.6	10.2
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	1.83	-31.2	-50.3	-49.4	12.3
Walk-through, north receive site	1.83	-29.9	-41.6	-39.7	15.1
Road drive, north receive site	1.83	-43.7	-42.0	-40.1	11.6
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	1.83	-56.8	-41.5	-26.0	22.2
Receiver site 2	1.83	-38.3	-60.8	-52.9	13.8



**Table 23. 2.4 GHz frequency band.**

Structure/Location	Freq. (GHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>Horizon West apartment (Boulder, CO)</b>					
Receiver site 1	2.445	−55.6	−17.9	−17.5	12.0
Receiver site 2	2.445	−61.0	−25.6	−24.8	9.6
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	2.445	−32.0	−52.0	−48.3	16.1
Walk-through, north receive site	2.445	−28.5	−43.1	−41.1	17.5
Road drive, north receive site	2.445	−39.3	−43.8	−41.8	12.1
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	2.445	−18.4	−61.9	−62.7	21.1
Receiver site 2	2.445	−52.4	−46.3	−39.1	13.7

**Table 24. 4.9 GHz frequency band.**

Structure/Location	Freq. (GHz)	Ref. level (dBm)	Median (dB)	Mean (dB)	Std. Dev. (dB)
<b>Horizon West apartment (Boulder, CO)</b>					
Receiver site 1	4.9	−44.8	−37.6	−36.3	13.6
Receiver site 2	4.9	−55.9	−30.8	−29.9	10.3
<b>Oil refinery (Commerce City, CO)</b>					
Walk-through, south receive site	4.9	−33.6	−54.8	−50.4	16.6
Walk-through, north receive site	4.9	−23.8	−50.1	−48.5	16.8
Road drive, north receive site	4.9	−36.5	−51.4	−48.2	11.4
<b>NIST laboratory (Boulder, CO)</b>					
Receiver site 1	4.9	−21.7	−61.9	−59.9	21.3
Receiver site 2	4.9	−59.3	−40.9	−37.3	9.0

The next two tables provide insight into some overall behavior trends. Table 25 lists the overall statistics computed on the standard deviation results from all the building measurements. For example, the second row contains the median values of the standard deviation computed for all the buildings across all the measured frequencies. The similar values of these overall statistics indicate that the standard deviation behaves in a very similar fashion across all the frequencies.

**Table 25. Statistics of the standard deviation behavior for all the buildings.**

Frequency Band:	50 MHz	150 MHz	225 MHz	450 MHz	900 MHz	1.8 GHz	2.4 GHz	4.9 GHz
Median	13.10	12.30	13.30	12.20	13.65	12.00	13.70	13.60
Mean	12.67	12.65	12.72	12.72	13.44	11.77	13.50	12.95
Maximum	18.40	19.20	20.30	20.70	22.30	19.60	17.50	16.80
Minimum	5.30	5.80	5.90	5.60	6.30	3.90	9.60	9.00
Std. Dev.	3.71	3.31	3.66	3.24	3.50	3.66	2.92	3.07

For a rough insight into the attenuation behavior, we examine mean values for eleven of the scenarios (see Table 26). Each scenario uses the receive site that typically provided the greatest dynamic range so as to reduce the impact of the limited dynamic range of the test equipment. Table 27 shows the mean values of the various frequencies for eleven scenarios listed in Table 26. Values in Table 27 were computed in decibels after subtracting the reference level.

Note that the combination of the reference level and the dynamic limitations of the test equipment can skew the statistics. The approximate noise floor provides an approximate value for the useable dynamic range. To obtain a rough idea of how close the mean signal is to the noise floor, we compute the difference between the mean signal level and the noise floor. The results for the eleven scenarios are shown in Table 28. In general, a greater difference implies less impact on the statistical results due to measured values at or below the noise floor. For example, the results for scenario six indicate mean signal levels very near the approximate noise floor, as indicated by a difference of less than 10 dB for all the frequencies. In contrast, scenario 10 indicates at least a 23 dB separation between the mean signal level and the noise floor for all frequencies.

**Table 26. Test scenarios used in examination of structure/building shielding.**

Selected test scenarios
1. New Orleans, LA apartment
2. Philadelphia, PA sports stadium: inside walk; vertical polarization
3. Colorado Springs, CO, CO hotel complex: first walk-through; receive site 1
4. Grocery store, Boulder, CO
5. NIST office, Gaithersburg, MD
6. Shopping mall, Bethesda, MD: receive site 1
7. Discovery office, Silver Spring, MD
8. Washington, DC convention center: receive site 3
9. Horizon West apartment, Boulder, CO: receive site 1
10. Oil refinery, Commerce City, CO: walk-through, north receive site
11. NIST laboratory, Boulder, CO: receive site 1

**Table 27. Mean values of scenarios used for structure/building attenuation statistics.**

Scenario	50 MHz	150 MHz	225 MHz	450 MHz	900 MHz	1.8 GHz	2.4 GHz	4.9 GHz
1	-37.5	-27.9	-33.1	-39.7	-34.2	-34.0	NA	NA
2	-32.8	-39.2	-34.2	-28.7	-27.2	-26.5	NA	NA
3	-58.0	-37.6	-39.5	-30.0	-34.1	NA	NA	NA
4	-43.1	-36.0	-43.0	-29.2	-33.8	-39.3	NA	NA
5	-62.1	-41.6	-44.1	-46.9	-57.7	-55.6	NA	NA
6	-47.2	-46.5	-49.9	-52.8	-44.6	-33.3	NA	NA
7	-63.7	-55.7	-60.3	-52.4	-70.4	-67.2	NA	NA
8	-65.3	-66.0	-62.3	-57.3	-66.4	-58.2	NA	NA
9	NA	-24.9	-25.9	-25.4	-27.0	-25.6	-17.5	-36.3
10	-50.3	-33.7	-34.1	-37.8	-42.7	-39.7	-41.1	-48.5
11	-50.2	-54.8	-43.3	-37.9	-28.9	-26	-62.7	-59.9

**Table 28. Difference in dB between the mean signal level and the noise floor for the scenarios used in the structure/building attenuation statistics.**

Scenario	50 MHz	150 MHz	225 MHz	450 MHz	900 MHz	1.8 GHz	2.4 GHz	4.9 GHz
1	21.5	19.1	17.9	12.3	30.8	16.0	NA	NA
2	16.2	33.8	25.8	27.3	24.8	13.5	NA	NA
3	18.0	18.4	19.5	24.0	21.9	NA	NA	NA
4	22.9	28.0	25.0	36.8	36.2	23.7	NA	NA
5	15.9	16.4	24.9	23.1	19.3	10.4	NA	NA
6	4.8	3.5	8.1	3.2	4.4	1.7	NA	NA
7	14.3	11.3	17.7	17.6	12.6	3.8	NA	NA
8	20.7	18.0	29.7	27.7	22.6	13.8	NA	NA
9	NA	66.1	69.1	67.6	57.0	48.4	27.5	8.5
10	23.7	45.3	46.9	42.2	34.3	33.3	36.9	24.5
11	16.8	33.2	24.7	28.1	35.1	19.0	20.3	20.1

Differences in building types make it difficult to provide clear general statements based on the collected data. However, we can observe some general trends.



First, examination of the standard deviation yields some interesting insights. In particular, if we exclude the first receiver site for the NIST laboratory in Boulder, CO, we see that the average standard deviation for the six lower frequency bands ranges from 11.8 dB to 13.4 dB. Limited data were collected for the upper two frequencies; but if we include those results, the upper limit of the range increases to 14.9 dB. Across all frequency bands, the range of maximum standard deviation covers 16.8 dB to 22.3 dB, with 22.3 dB occurring at 900 MHz. The minimum standard deviation values range from 3.9 dB to 12.1 dB, with 3.9 dB occurring at 1.8 GHz.

Second, in almost all cases, the median value for the power received is less than the average power received. The typical difference is between 2 dB to 3 dB. This suggests that median value may be a better measure for representing the general behavior of the building, or at least a more conservative performance measure.

Third, the histograms (which approximate PDFs) and the empirical CDFs appear to follow no typical density function. To some extent, each individual test case will generate a unique density. However, the data seem not to suggest any obvious average or best approximation density that could be used as a collective representation of the buildings.

The data presented in this report aid in understanding the issues faced with first responders communicating into and within large building structures. For example, the large amount of attenuation for the signals coupling into the different structures indicates to system designers what a communication link must overcome in order to have a reliable system. In addition, the measured signal variability indicates the dynamic environment these different buildings present to a communication system.

The results in this report are the fourth in a series of reports detailing experiments performed by NIST in order to better understand the first responder radio propagation environment. The first three reports cover implosion experiments performed in three different building structures, an apartment building in New Orleans, LA, a large sports stadium (the "Veterans Stadium") in Philadelphia, PA, and a convention center in Washington, DC. Other experiments at different frequencies in other building structures are being performed and will be published separately. We are also performing measurement to simulate and test the performance of ad-hoc networks in various building structures, and the results of these experiments will also be published separately.

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Disclaimer: Mention of any company names serves only for identification, and does not constitute or imply NIST endorsement of such a company or of its products.

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## 9. Figures



Figure 1. Typical transmitters used for the four lower frequency bands.



Figure 2. Transmitters used for the higher frequency bands.

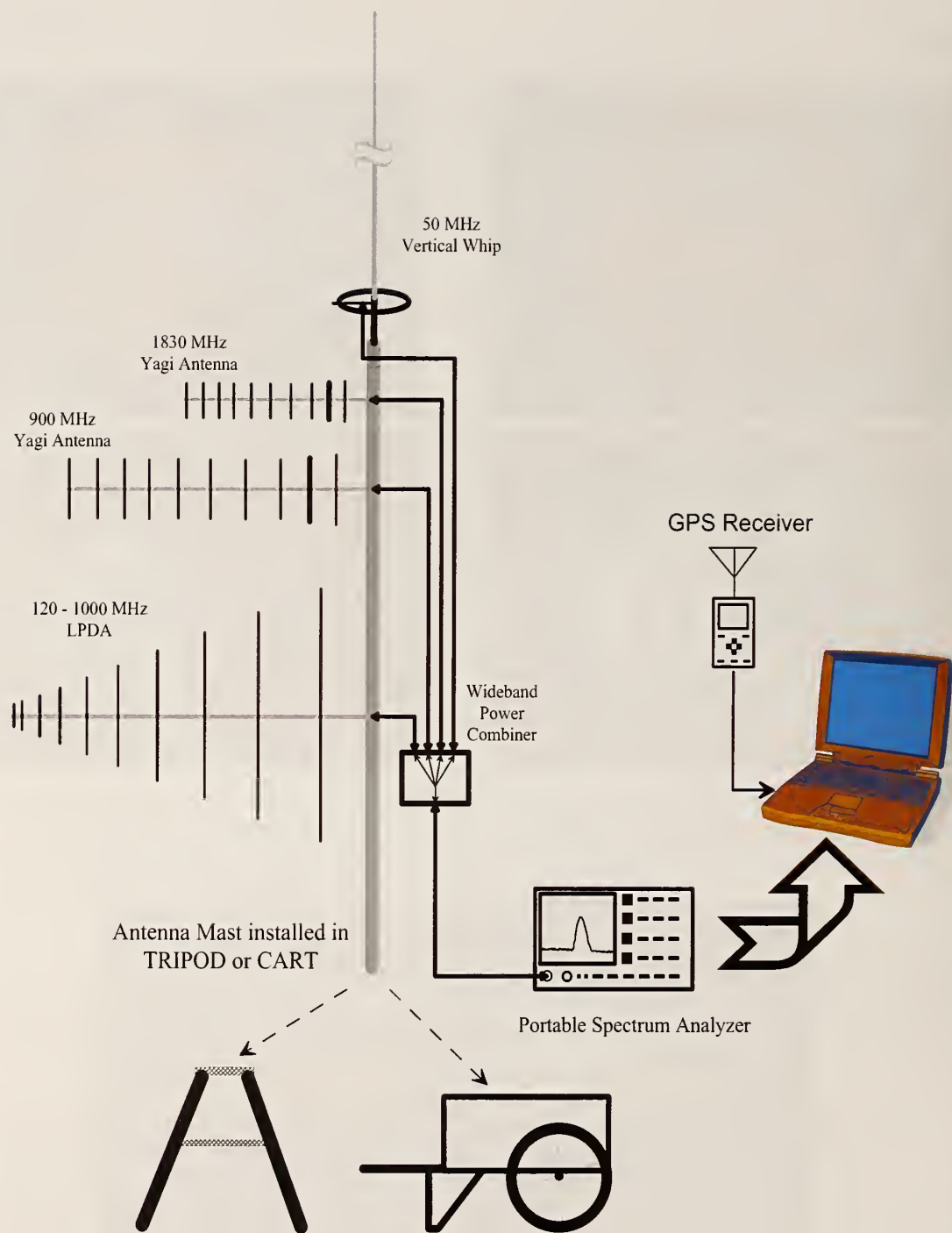


Figure 3. Schematic of the receiving system for the building penetration and field-mapping experiments.



Figure 4. Antennas mounted on a tripod.



Figure 5. Antennas mounted on the mobile cart.





Figure 6. The New Orleans, LA Fisher apartment building.



Figure 7. Inside the New Orleans, LA apartment building.

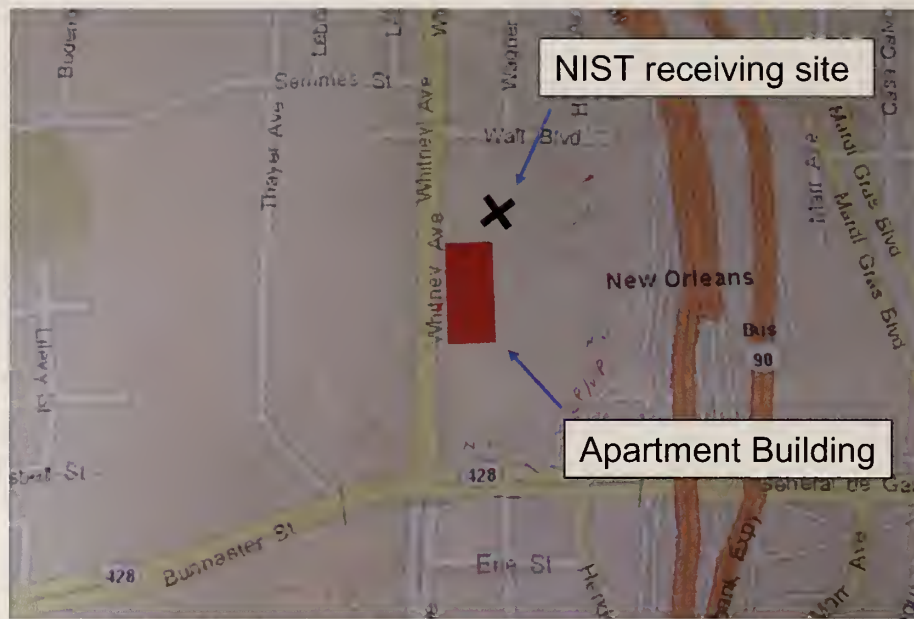


Figure 8. Receiver location and layout for the New Orleans, LA apartment building experiments.





Figure 9. The Veterans Stadium in Philadelphia, PA.



Figure 10. Inside the Veterans Stadium.



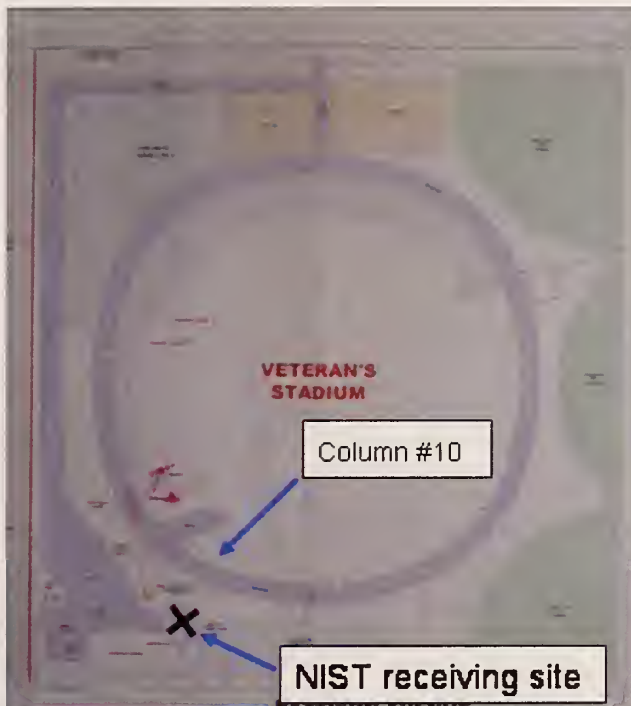


Figure 11. Receiver location and layout for the stadium experiments.

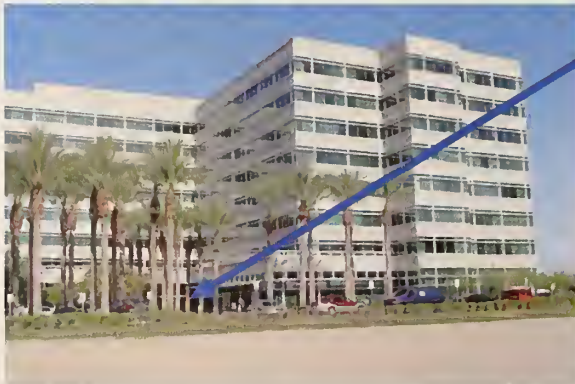




Figure 12. The office building in Phoenix, AZ.



Figure 13. Inside the office building in Phoenix, AZ.



NIST receiving site

Figure 14. Receiver location and layout for the Phoenix, AZ office building.





Figure 15. The hotel complex in Colorado Springs, CO, CO.



Figure 16. Inside the hotel complex in Colorado Springs, CO, CO.





Figure 17. Receiver location and layout for the Colorado Springs, CO hotel complex.





Figure 18. The grocery store in Boulder, CO.

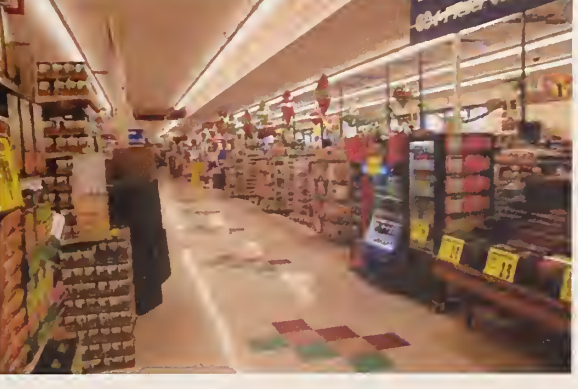


Figure 19. Inside the grocery store in Boulder, CO.





Figure 20. Receiver location and layout for the Boulder, CO grocery store.





Figure 21. The NIST office building in Gaithersburg, MD.



Figure 22. Receiver location and layout for the NIST Gaithersburg, MD office building.



Figure 23. The shopping mall in Bethesda, MD.





Figure 24. Inside the shopping mall in Bethesda, MD.



Figure 25. Receiver location and layout for the Bethesda, MD shopping mall.



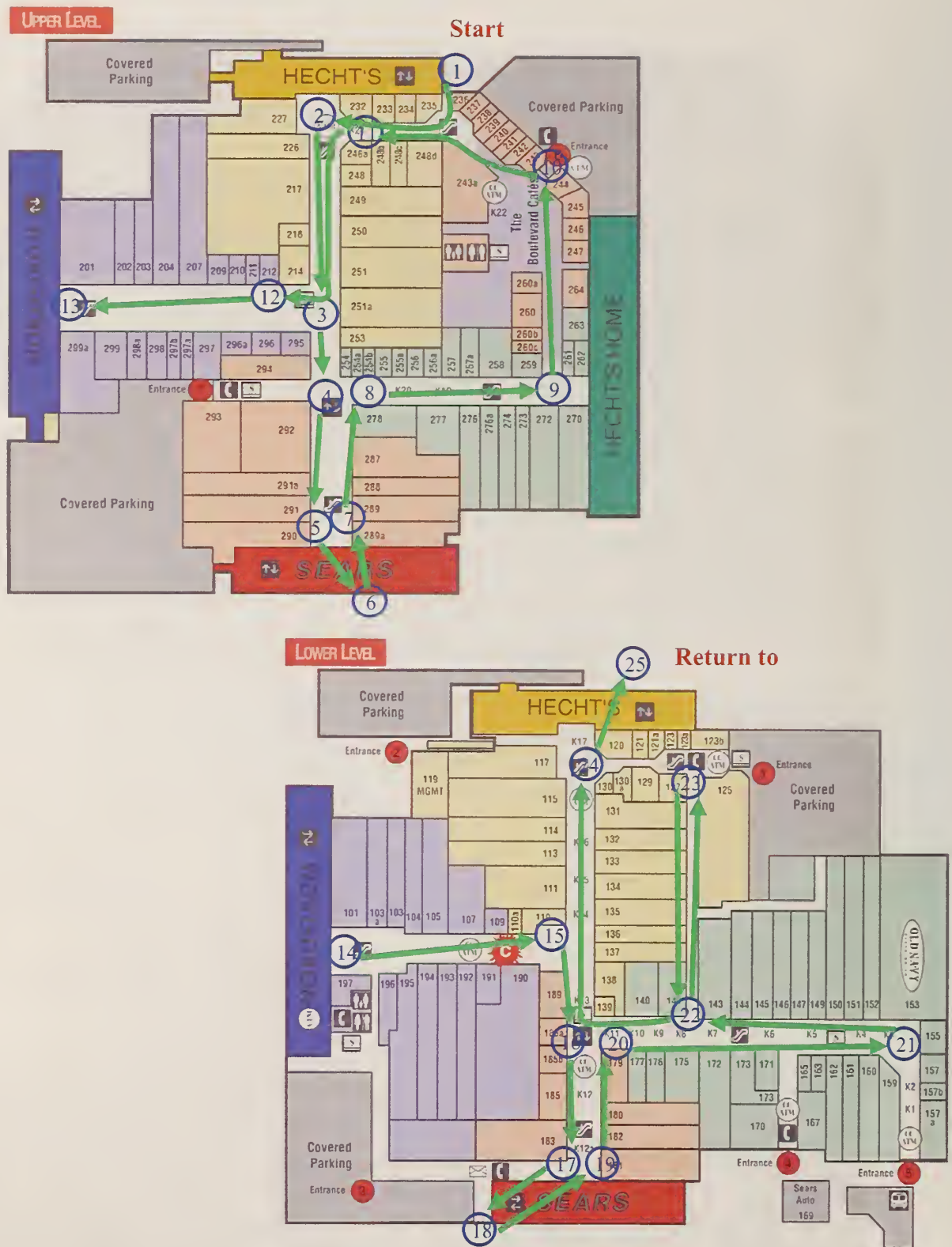


Figure 26. Upper and lower level floor plan with the predetermined locations on both levels of the shopping mall. The green arrows in the figure represent the actual paths that were walked.



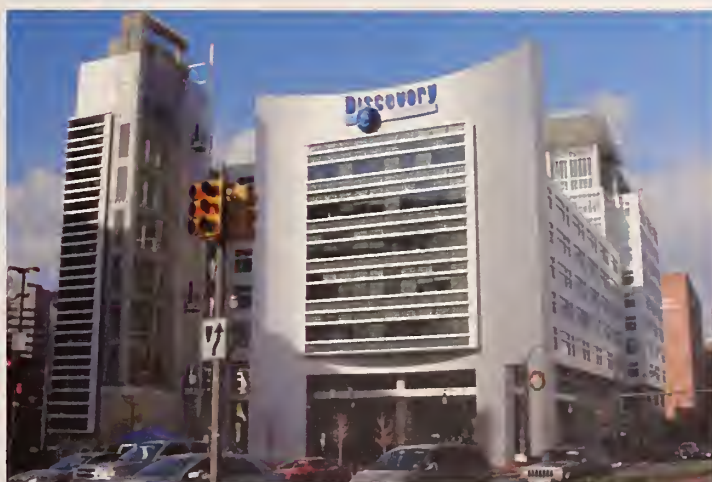


Figure 27. The Discovery office building in Silver Springs, MD.



Figure 28. Inside the Discovery office building in Silver Springs, MD.



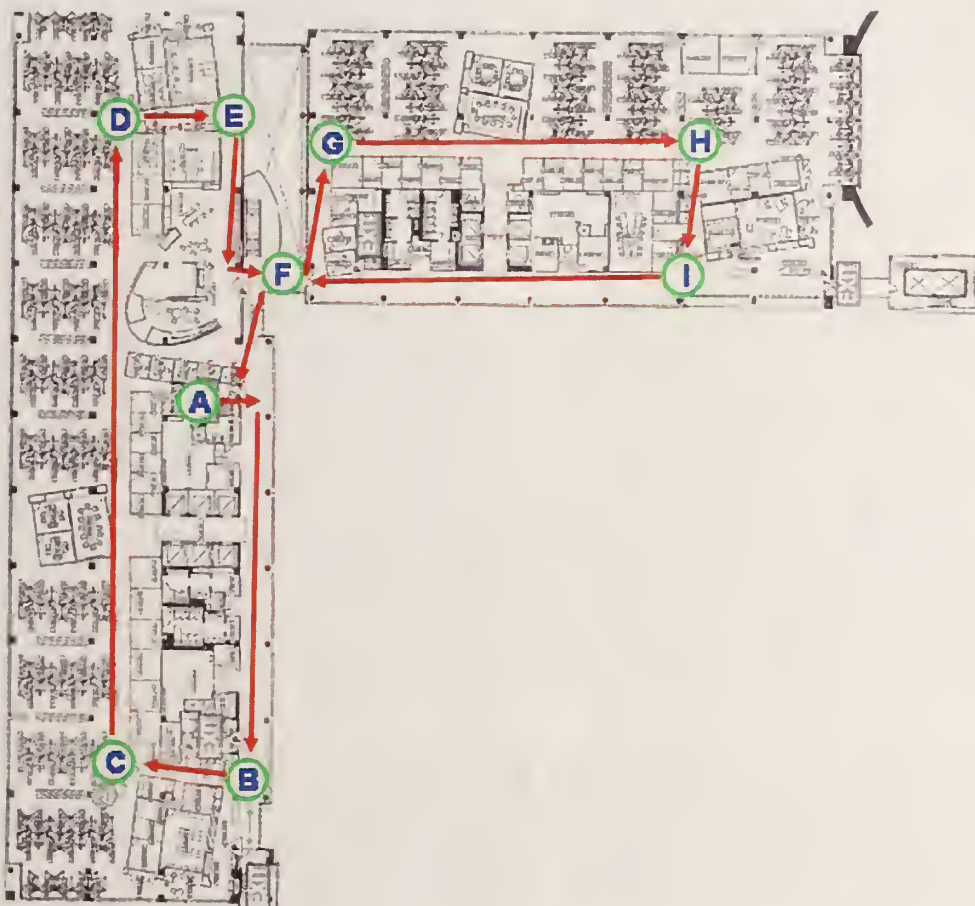


Figure 29: Building layout and measurement locations for the Discovery building.



Receiving site



Figure 30. Receiver location and layout for the Discovery office building in Silver Springs, MD.



Figure 31. The convention center in Washington, DC.





Figure 32. Inside the convention center in Washington, DC.





Figure 33. Receiver location and layout for the convention center in Washington, DC.

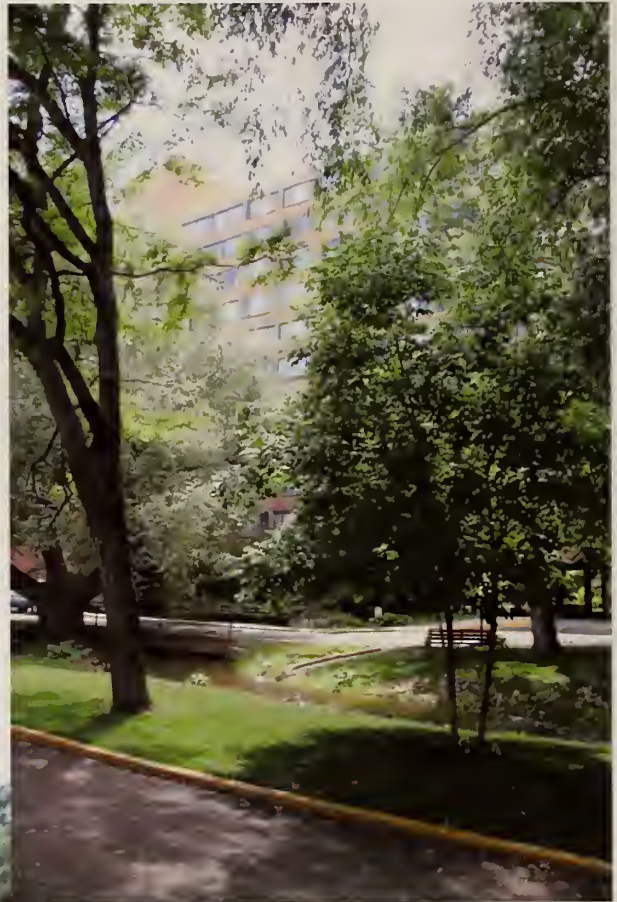


Figure 34. Horizon West apartment building in Boulder, CO.



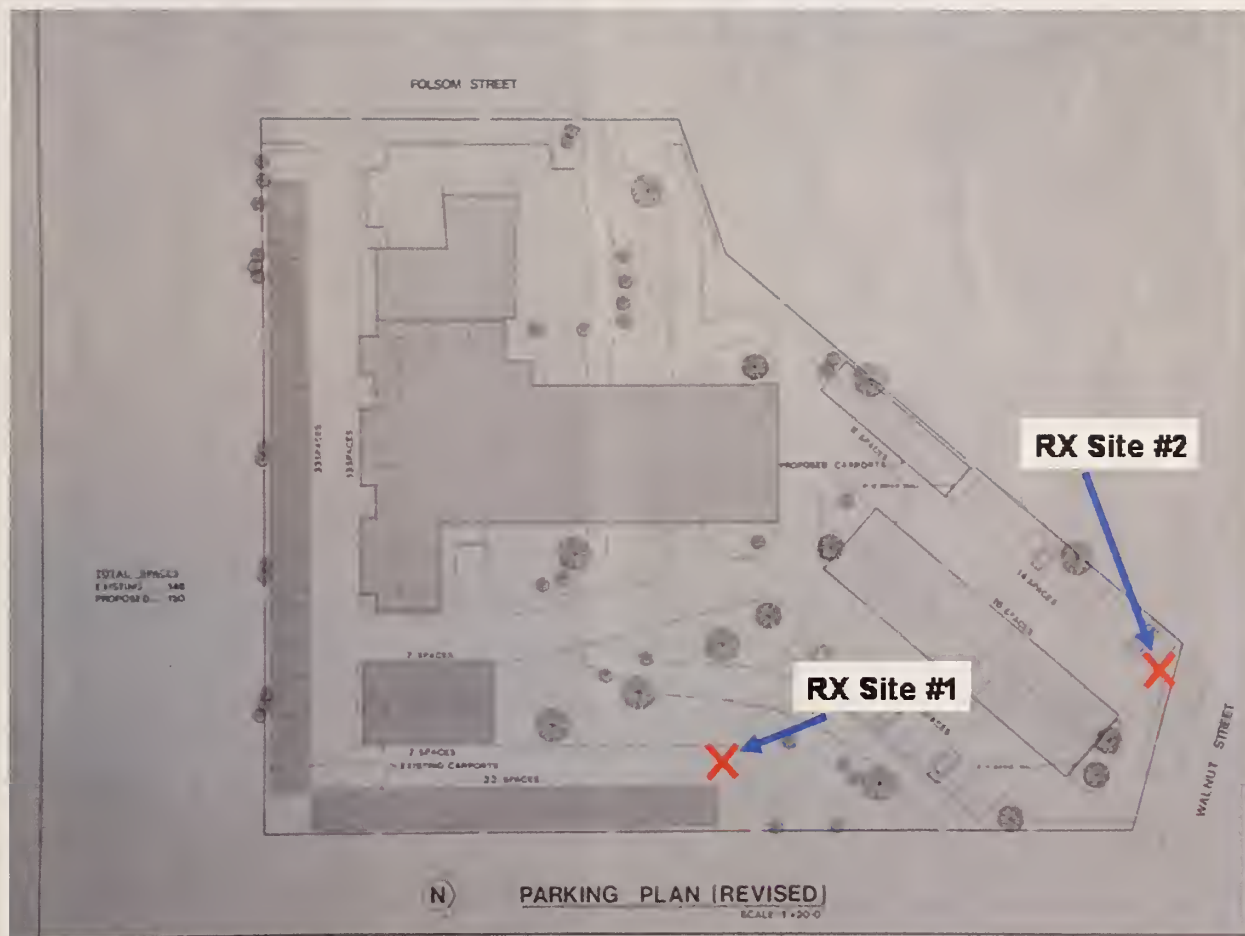


Figure 35. Transmitter locations for Horizon West.





Figure 36. Receiver setups for Horizon West apartment building in Boulder, CO.

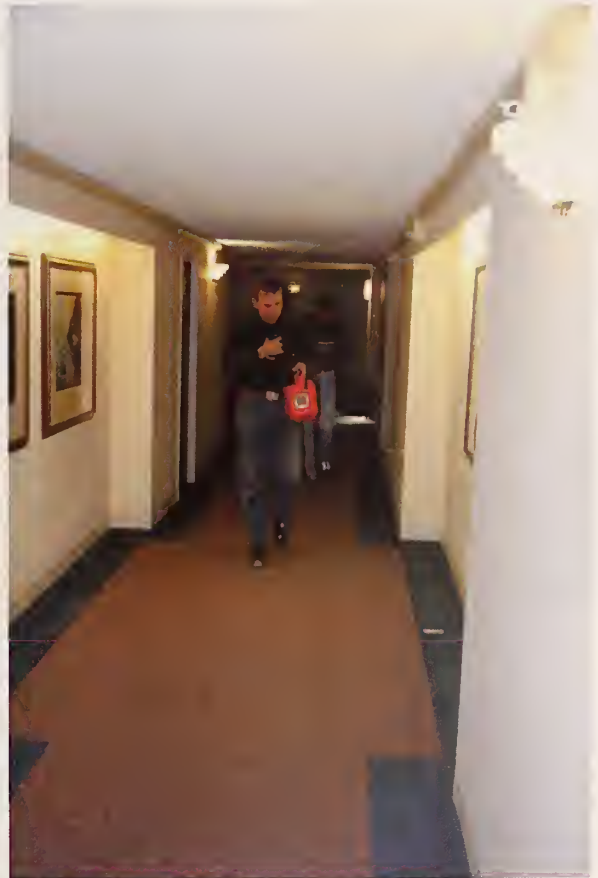


Figure 37. Inside the Horizon West apartment building in Boulder, CO.



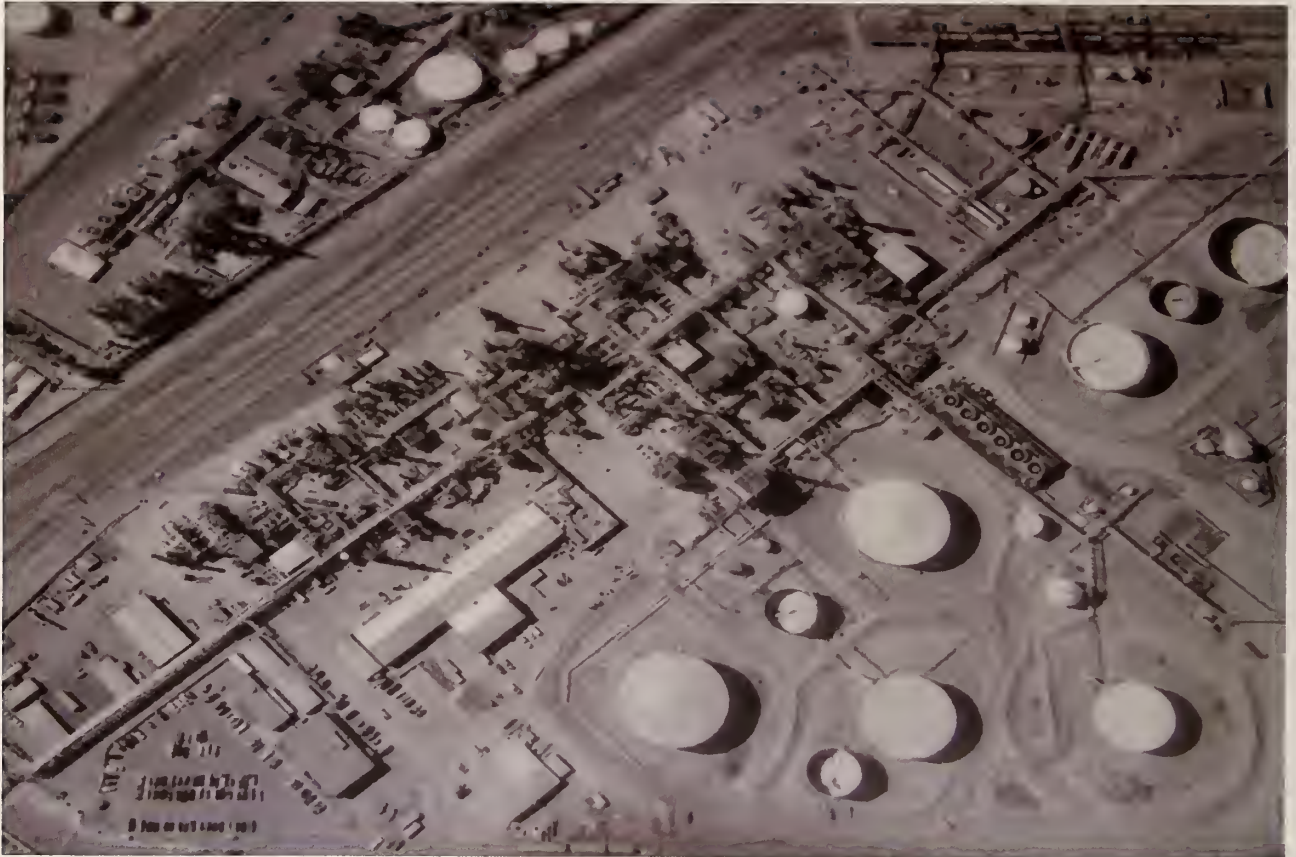


Figure 38. Overview of the Inside the SUNCOR oil refinery in Commerce City, CO.





Figure 39. The receiver locations at the SUNCOR oil refinery in Commerce City, CO.



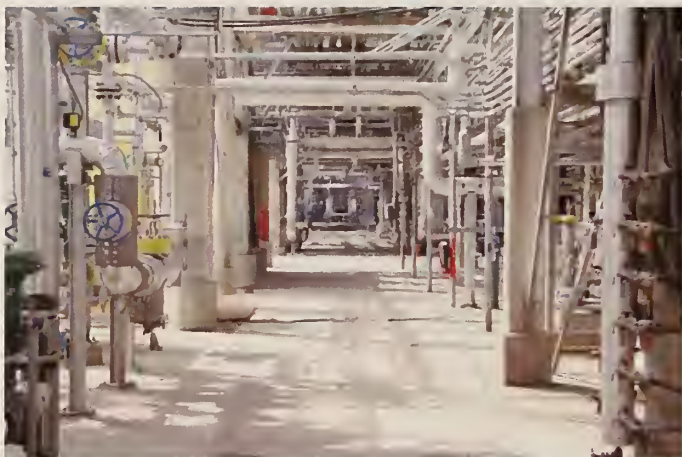


Figure 40. Inside the SUNCOR oil refinery in Commerce City, CO.



Figure 41. The driven section of the data collection process at the SUNCOR oil refinery.



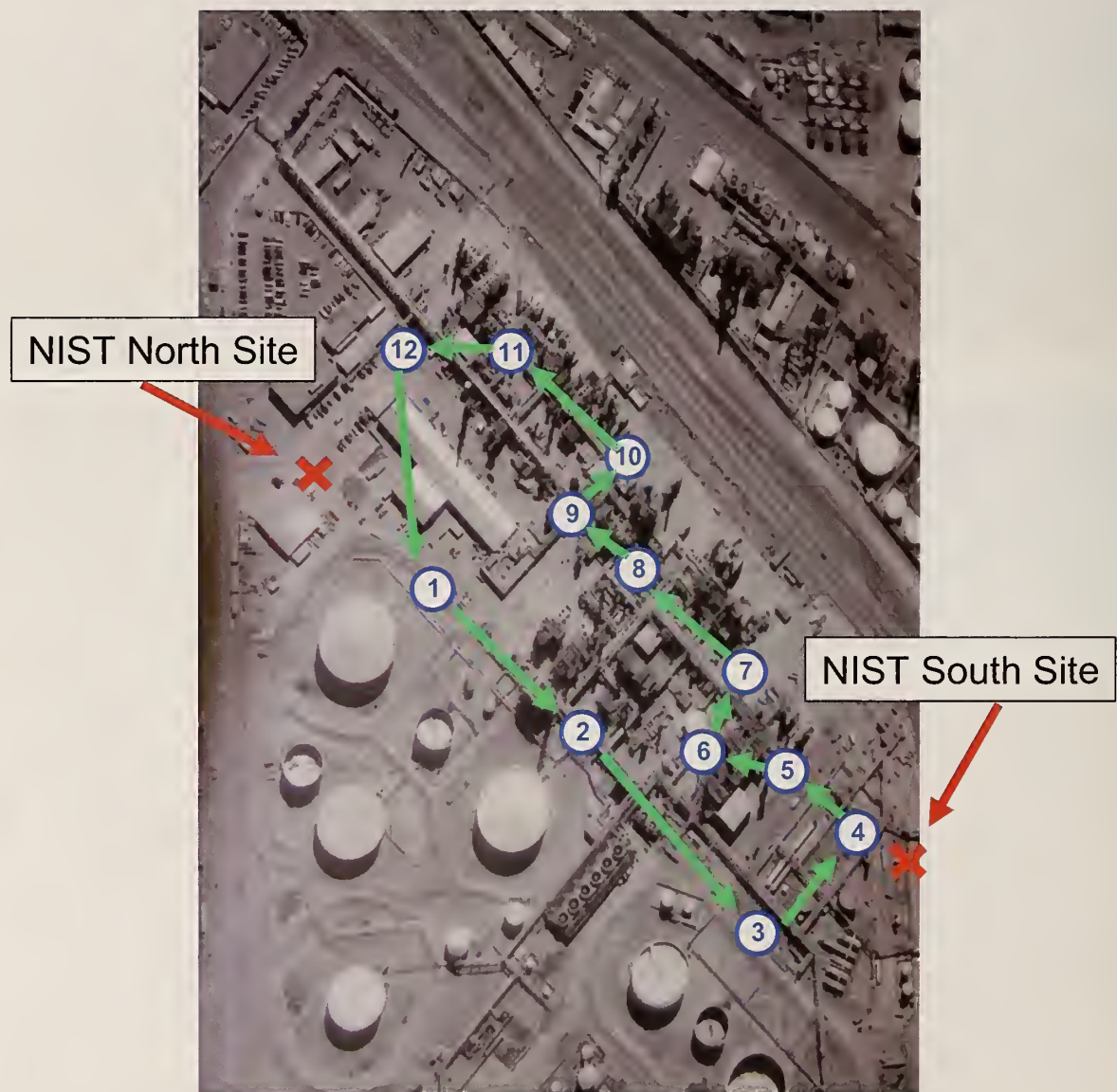


Figure 42. Receiver location and layout for the Commerce City, CO oil refinery.



Figure 43. NIST main building (the Radio Building) in Boulder, CO.





Figure 44. The receiver setups for the NIST's laboratories in Boulder, CO.





Figure 45. Receiver location and layout for the Boulder, CO laboratories.

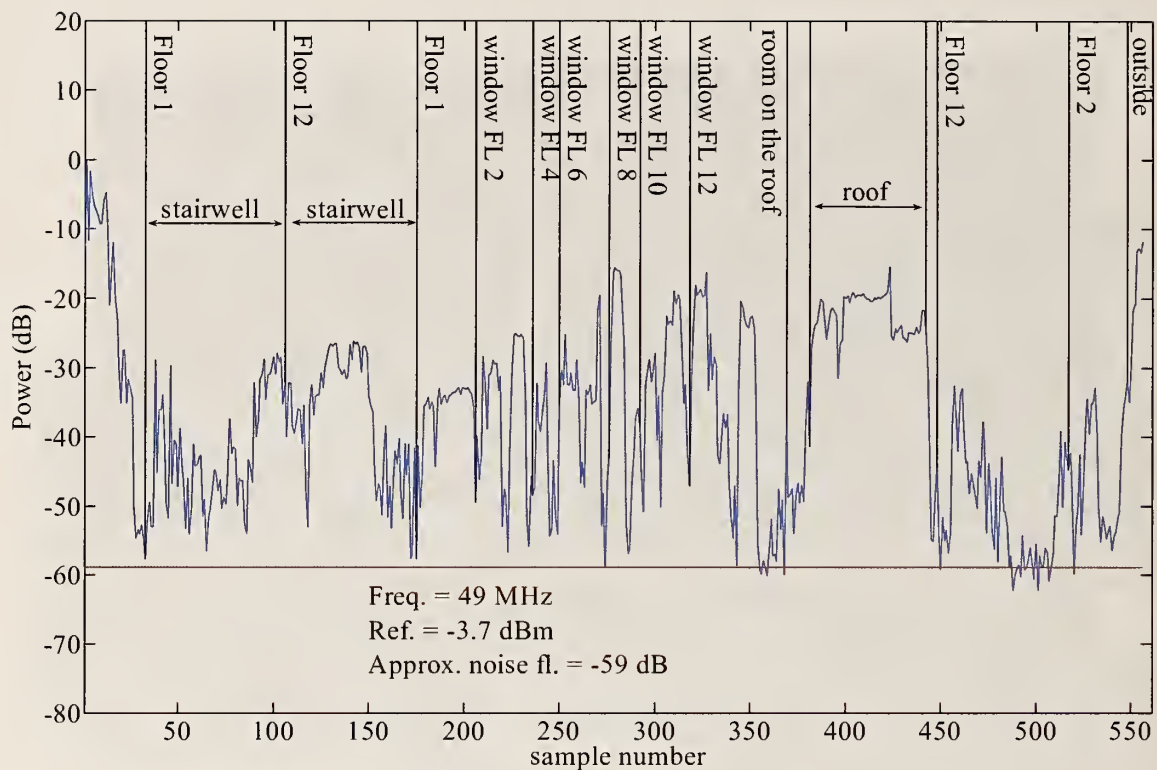


Figure 46. New Orleans, LA apartment building walk-through at 49.60 MHz.

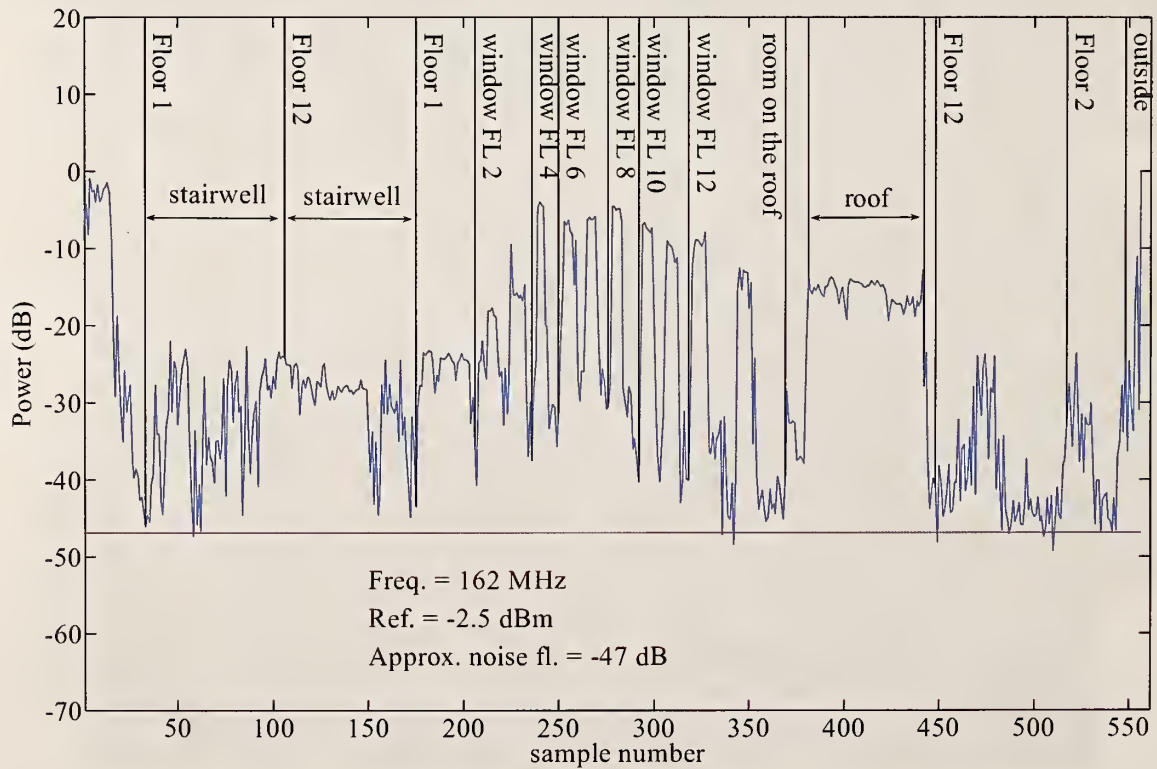


Figure 47. New Orleans, LA apartment building walk-through at 162.00 MHz.

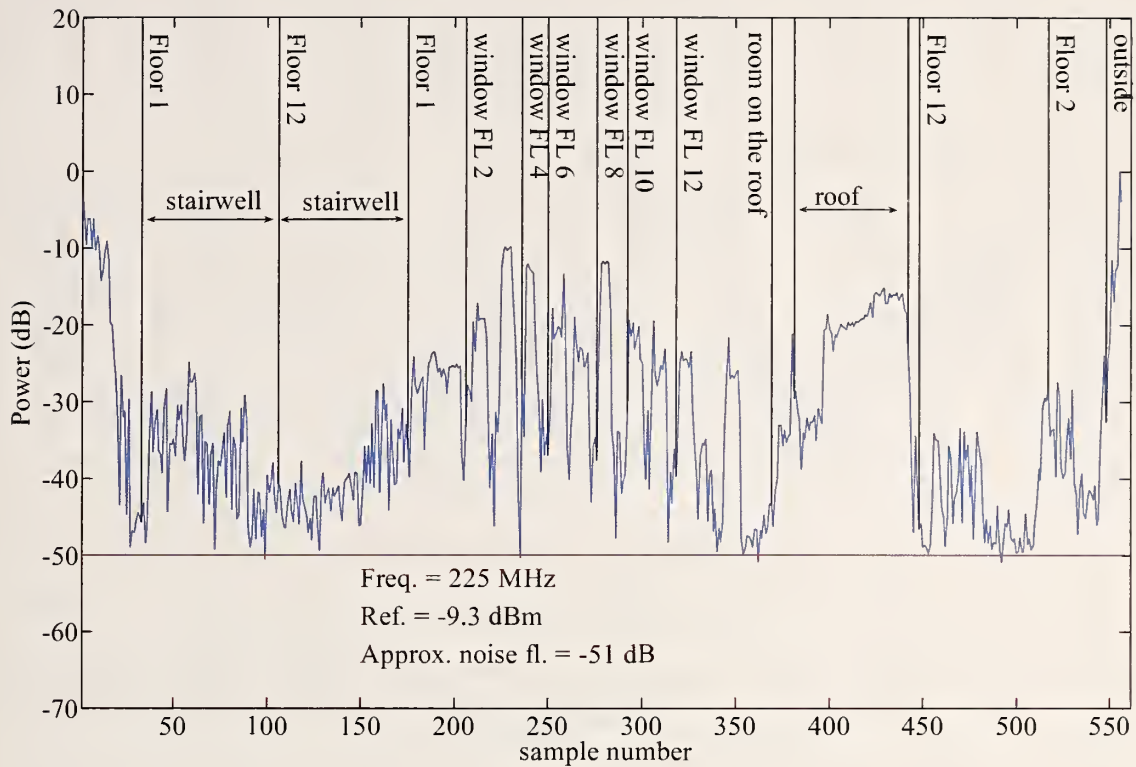


Figure 48. New Orleans, LA apartment building walk-through at 225.375 MHz.

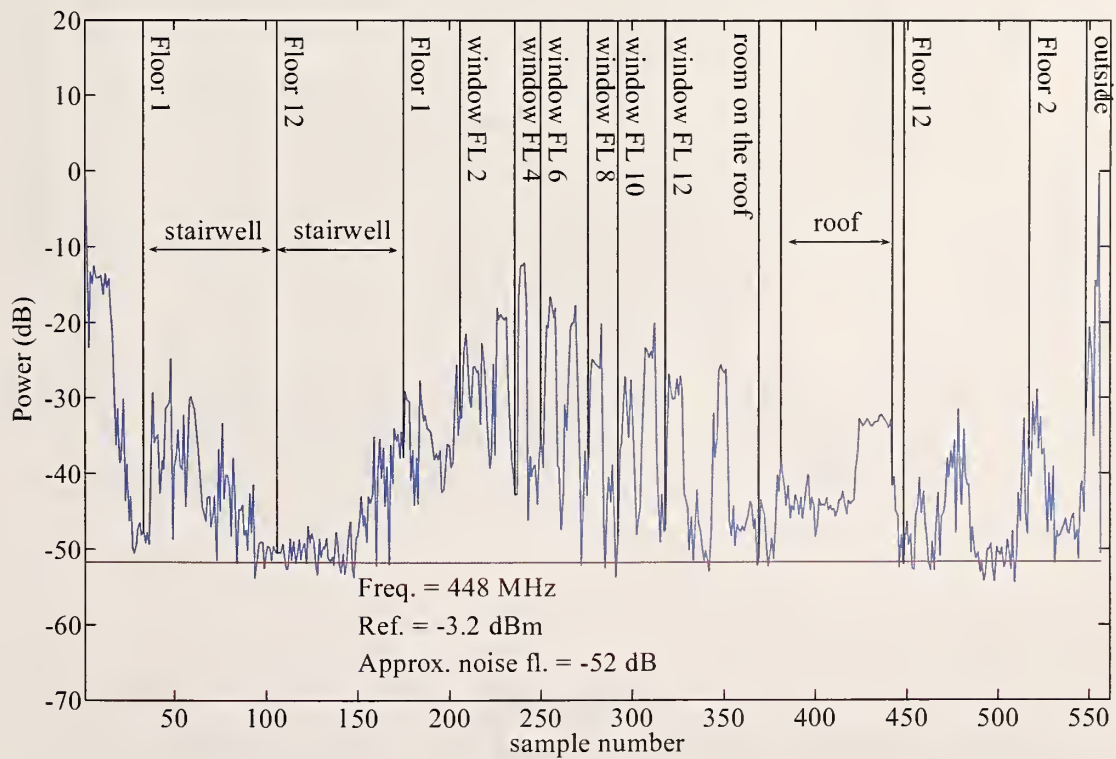


Figure 49. New Orleans, LA apartment building walk-through at 448.60 MHz.



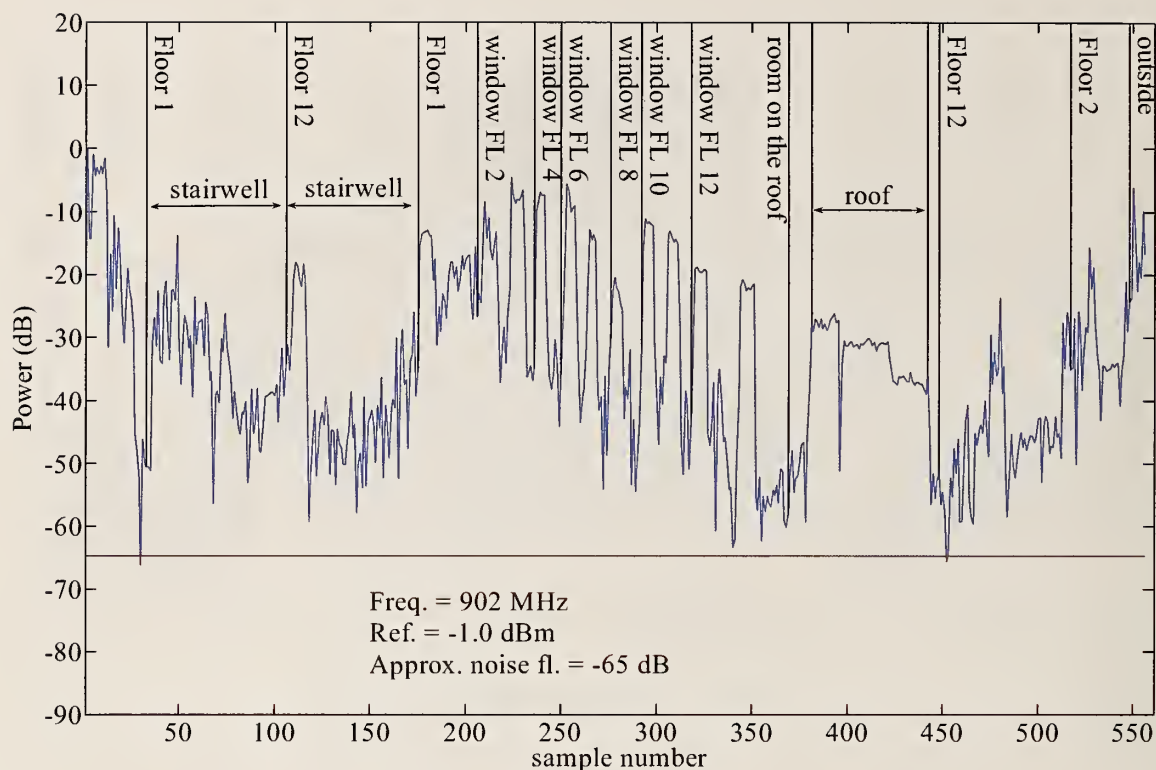


Figure 50. New Orleans, LA apartment building walk-through at 902.60 MHz

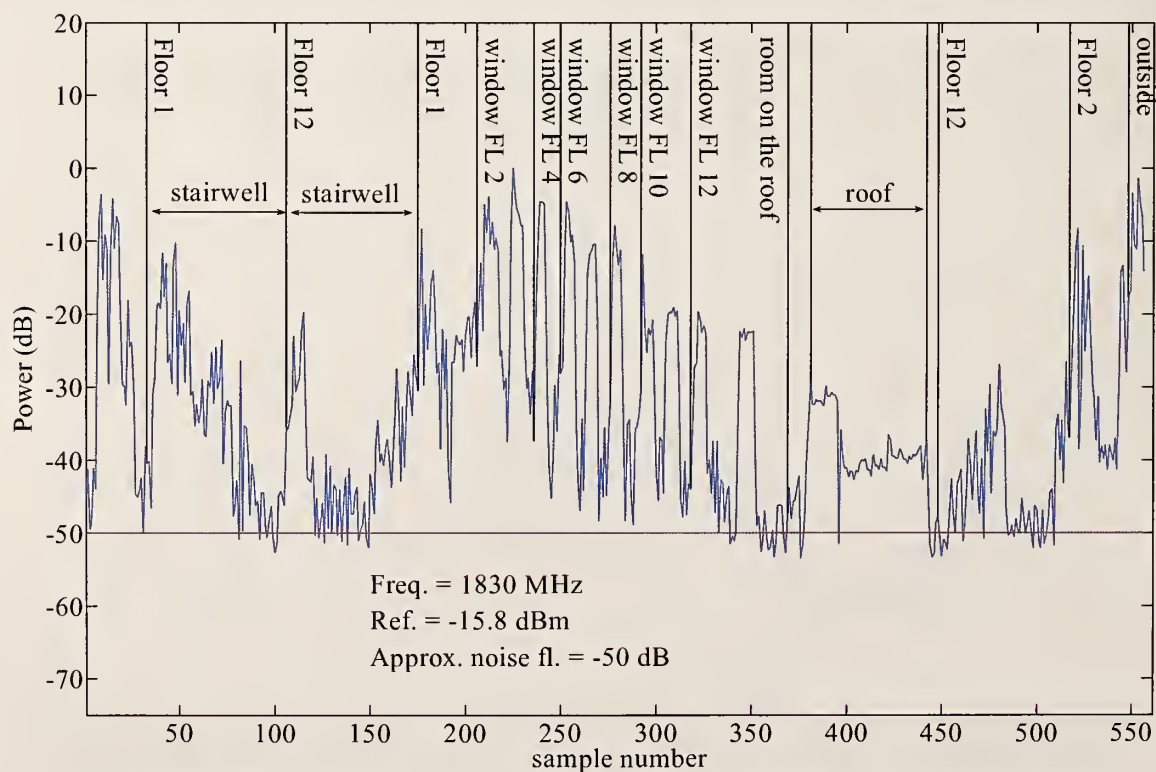


Figure 51. New Orleans, LA apartment building walk-through at 1832.50 MHz.

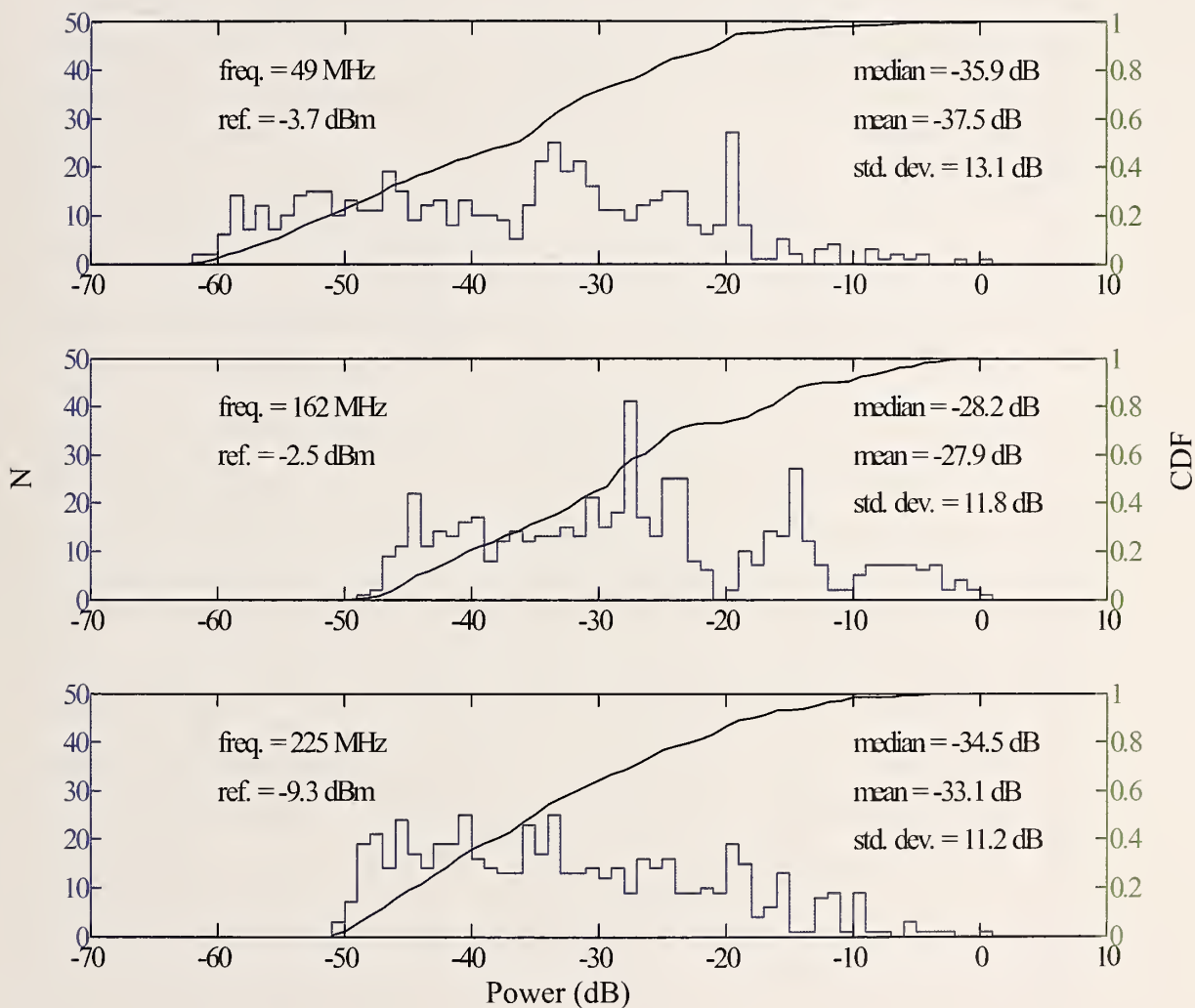


Figure 52. New Orleans, LA apartment building statistics, histograms, and empirical CDF for walk-through data at 49.60, 162.00, and 225.375 MHz.

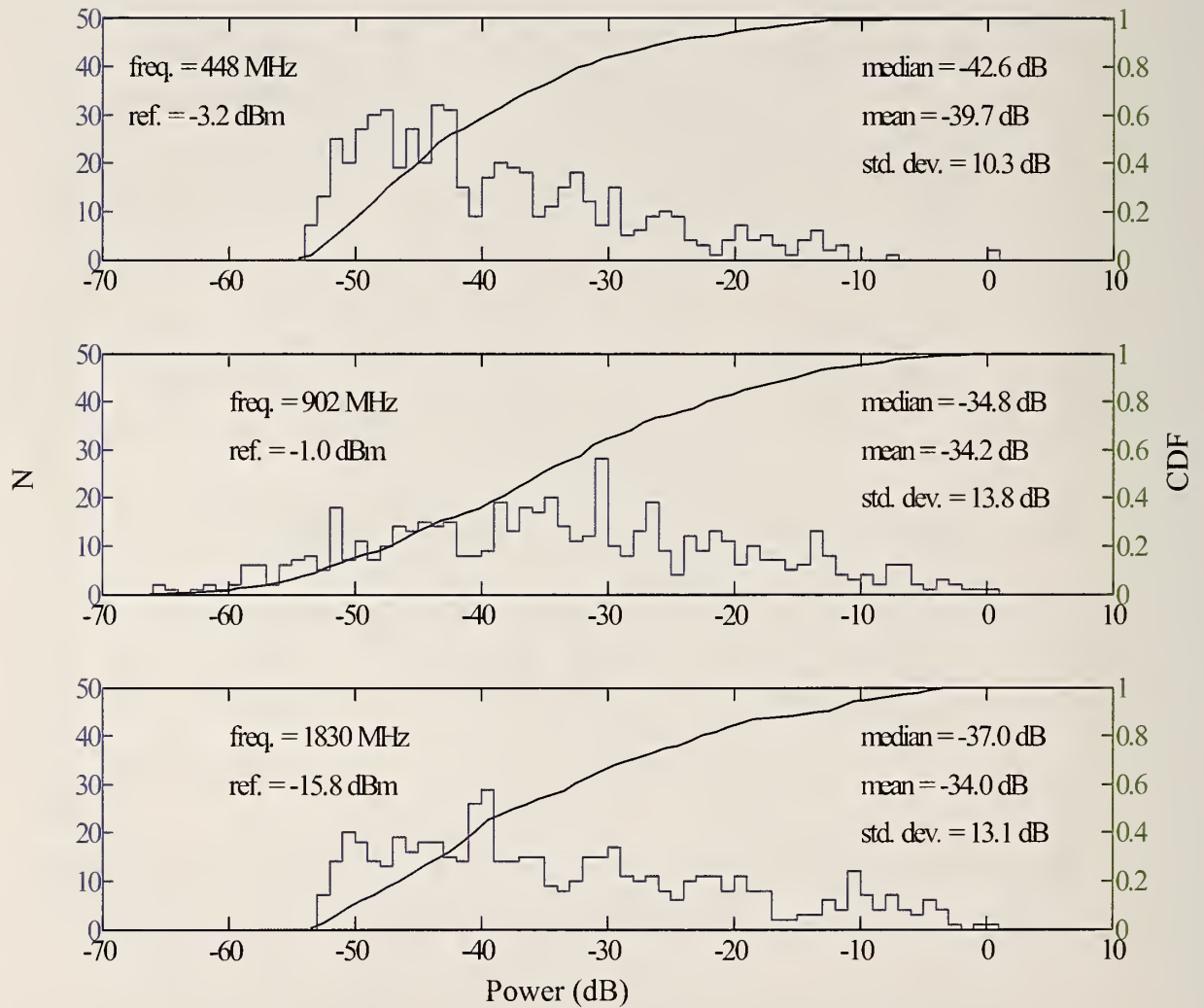


Figure 53. New Orleans, LA apartment building statistics, histograms, and empirical CDF for walk-through data at 448.60, 902.60, and 1832.50 MHz.



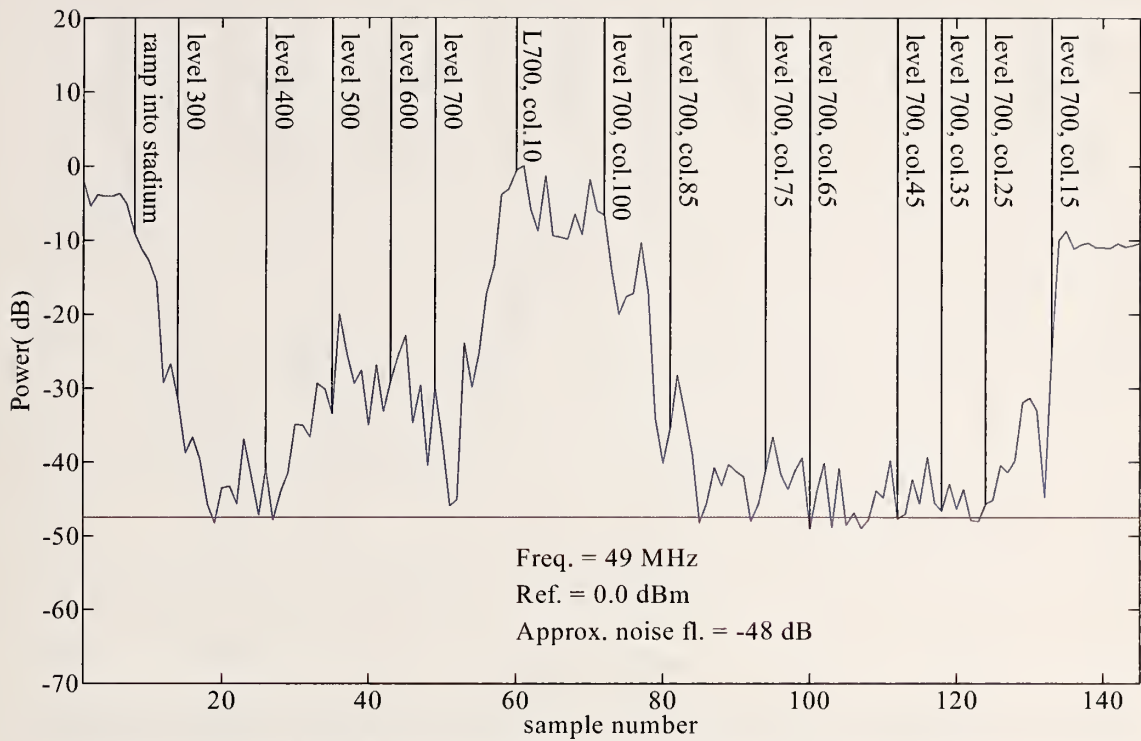


Figure 54. Philadelphia, PA sports stadium first inside walk at 49.60 MHz; horizontal polarization.

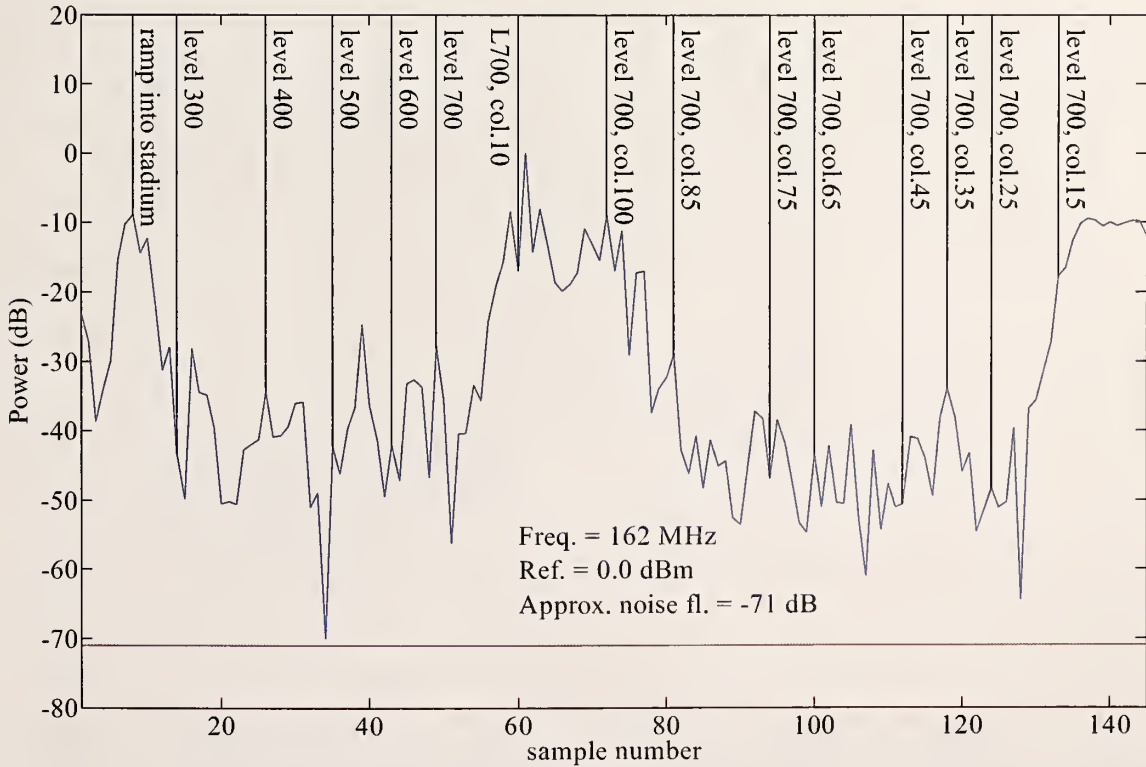


Figure 55. Philadelphia, PA sports stadium first inside walk at 162.09 MHz; horizontal polarization.

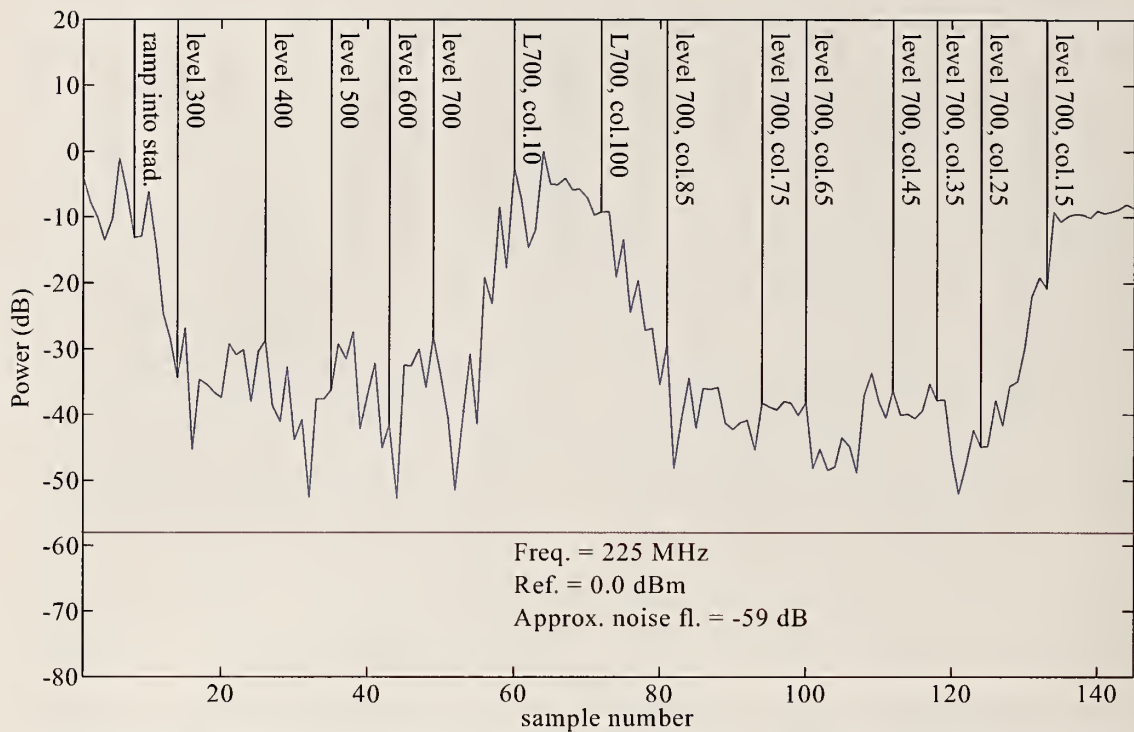


Figure 56. Philadelphia, PA sports stadium first inside walk at 225.30 MHz; horizontal polarization.

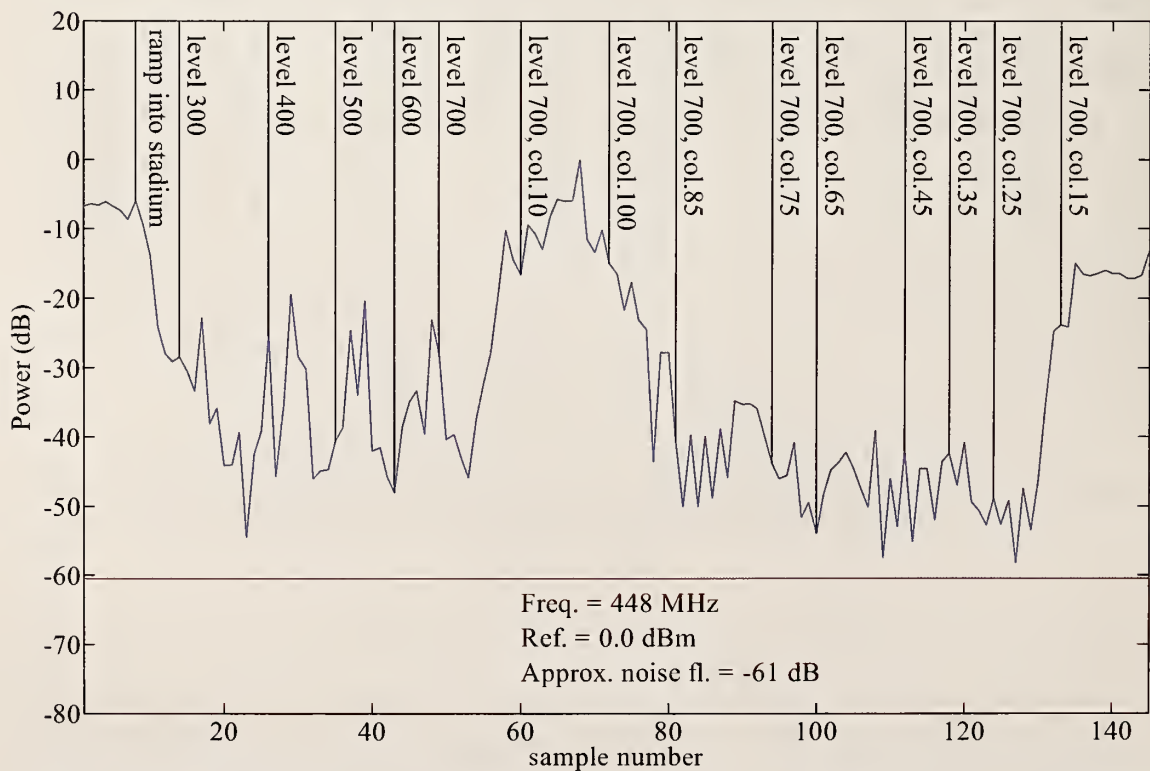


Figure 57. Philadelphia, PA sports stadium first inside walk at 448.50 MHz; horizontal polarization.

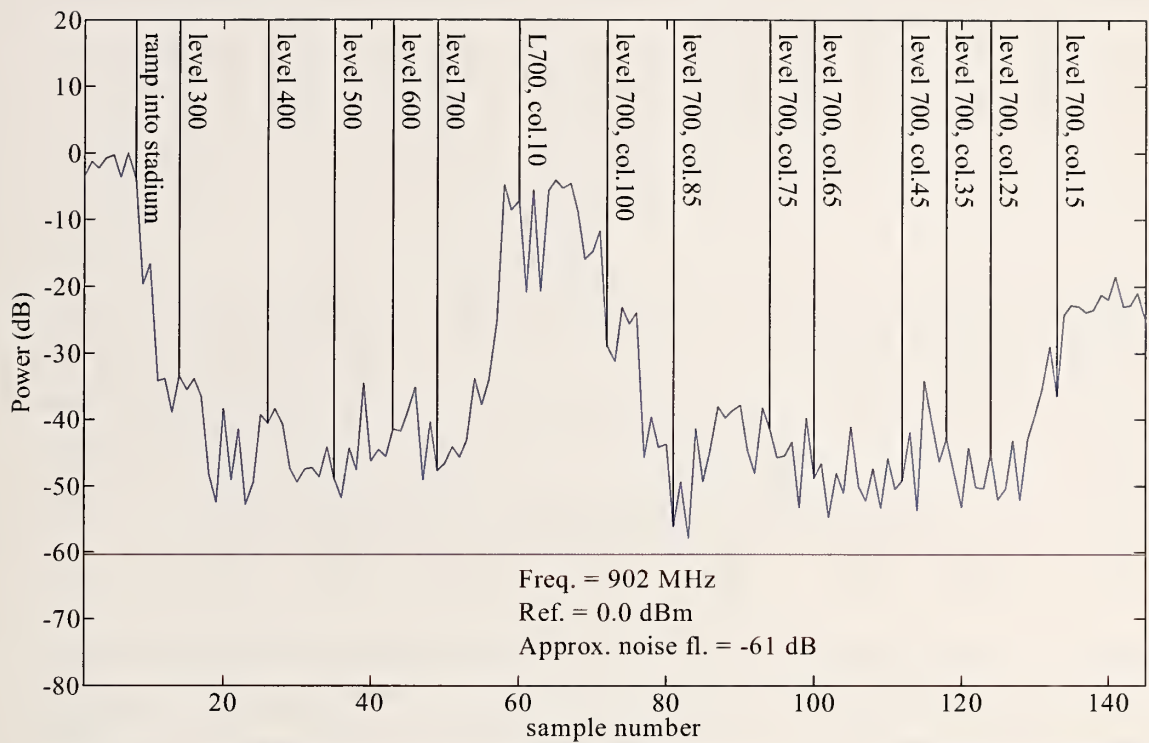


Figure 58. Philadelphia, PA sports stadium first inside walk at 902.45 MHz; horizontal polarization.

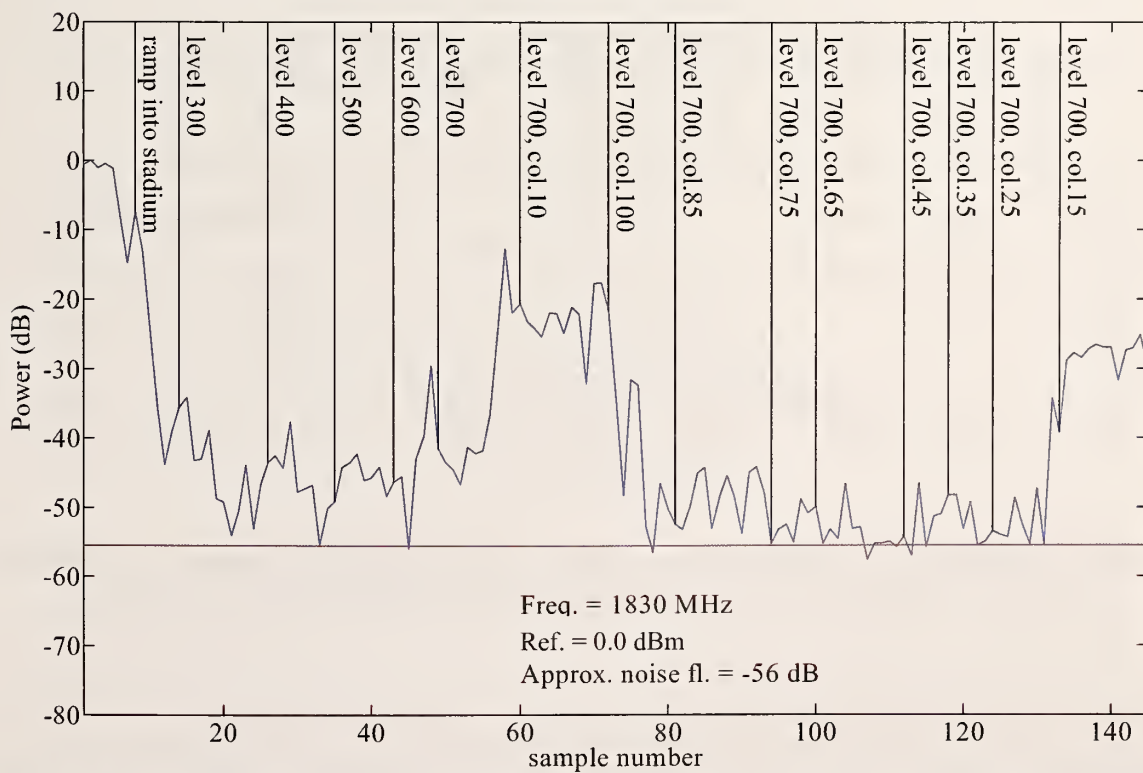


Figure 59. Philadelphia sports stadium first inside walk at 1832.00 MHz; horizontal polarization.



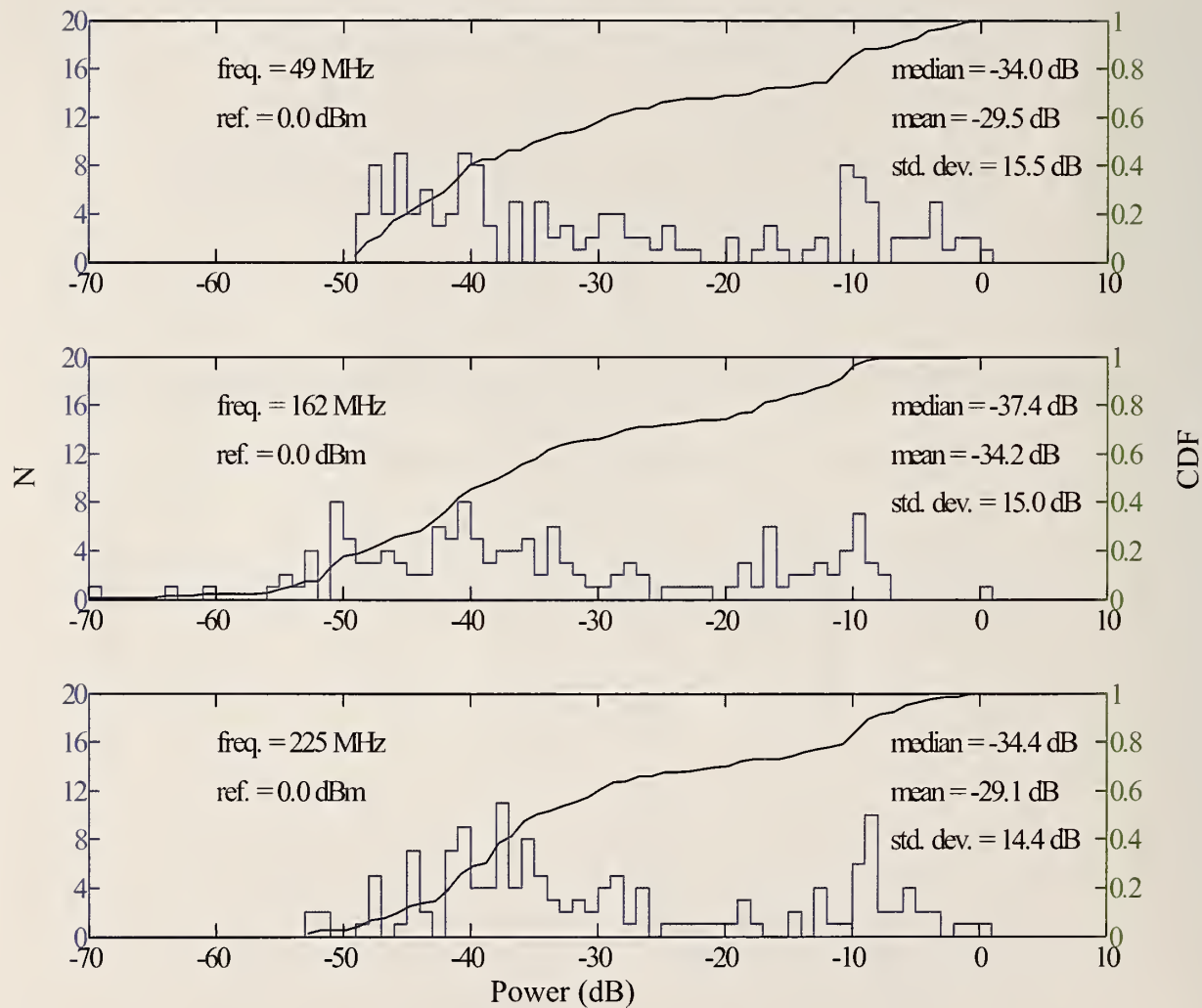


Figure 60. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for first inside walk data at 49.60, 162.09, and 225.30 MHz; horizontal polarization.

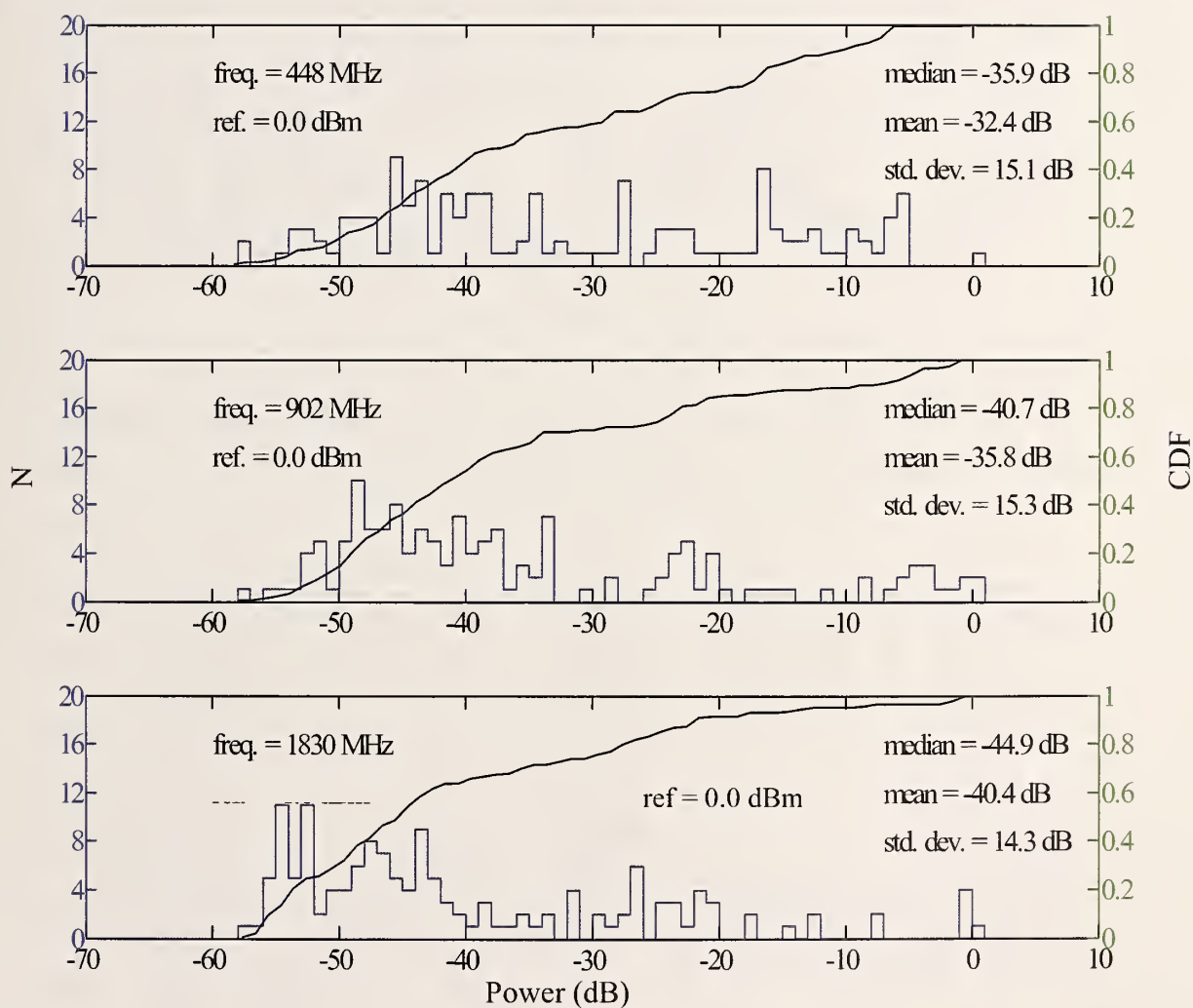


Figure 61. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for First inside walk data at 448.50, 902.45, and 1832.00 MHz; horizontal polarization.

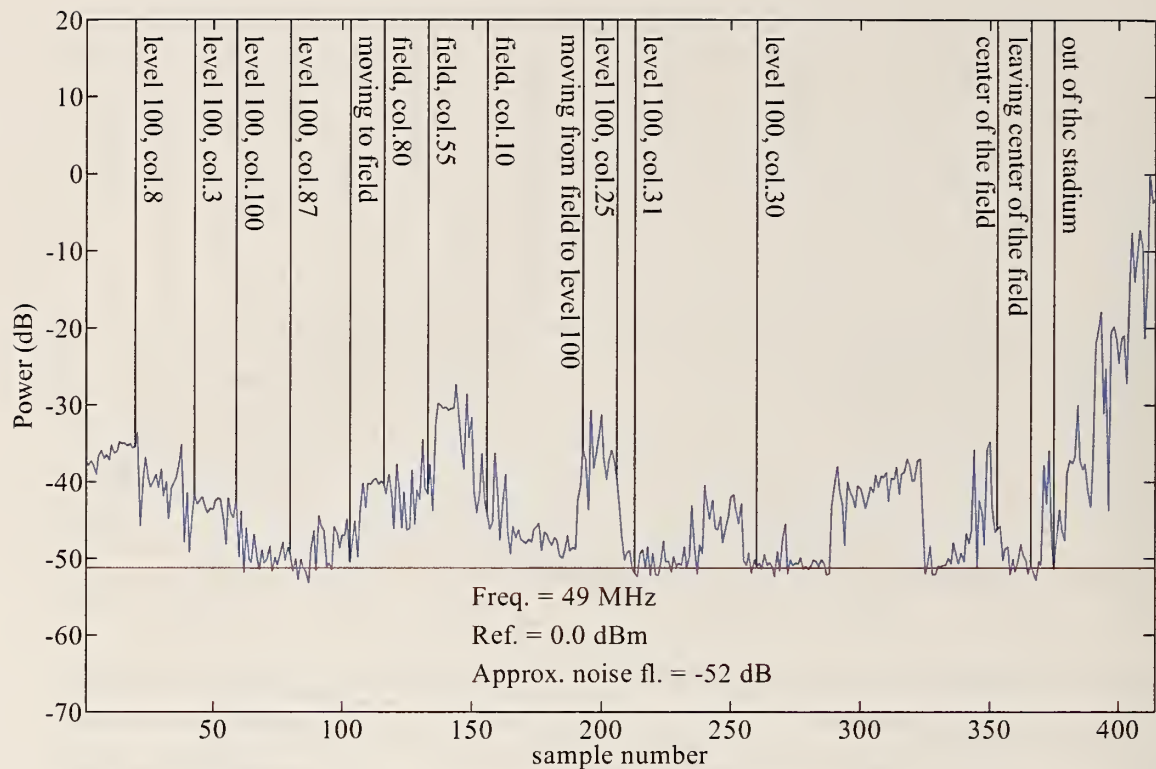


Figure 62. Philadelphia, PA sports stadium second inside walk at 49.60 MHz; horizontal polarization.

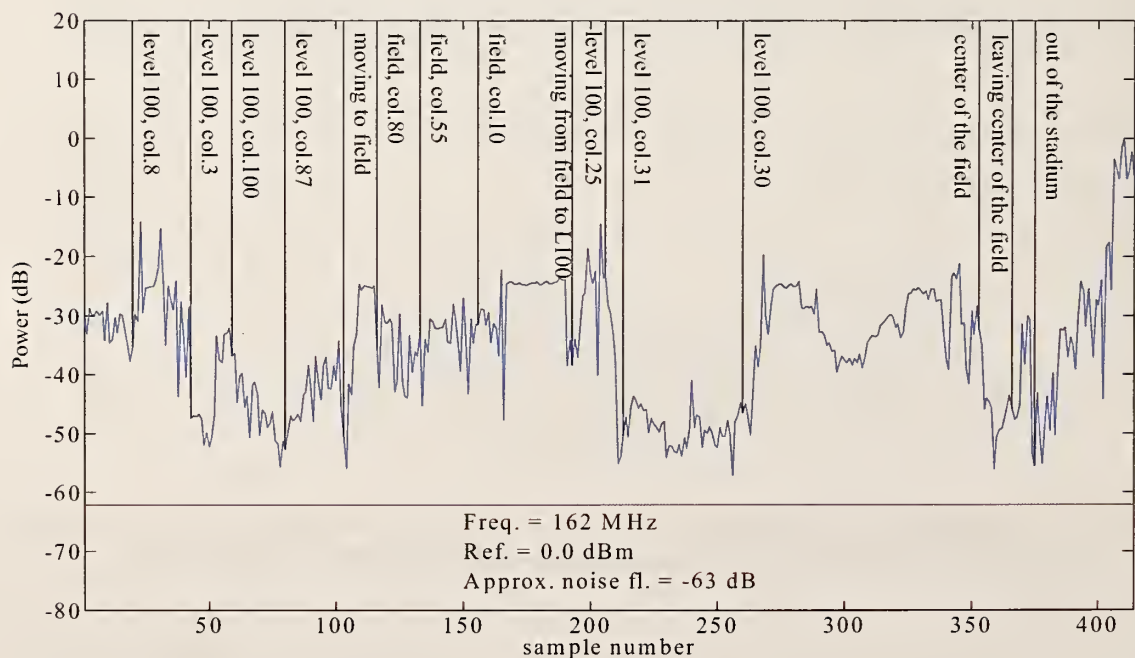


Figure 63. Philadelphia, PA sports stadium second inside walk at 162.09 MHz; horizontal polarization.



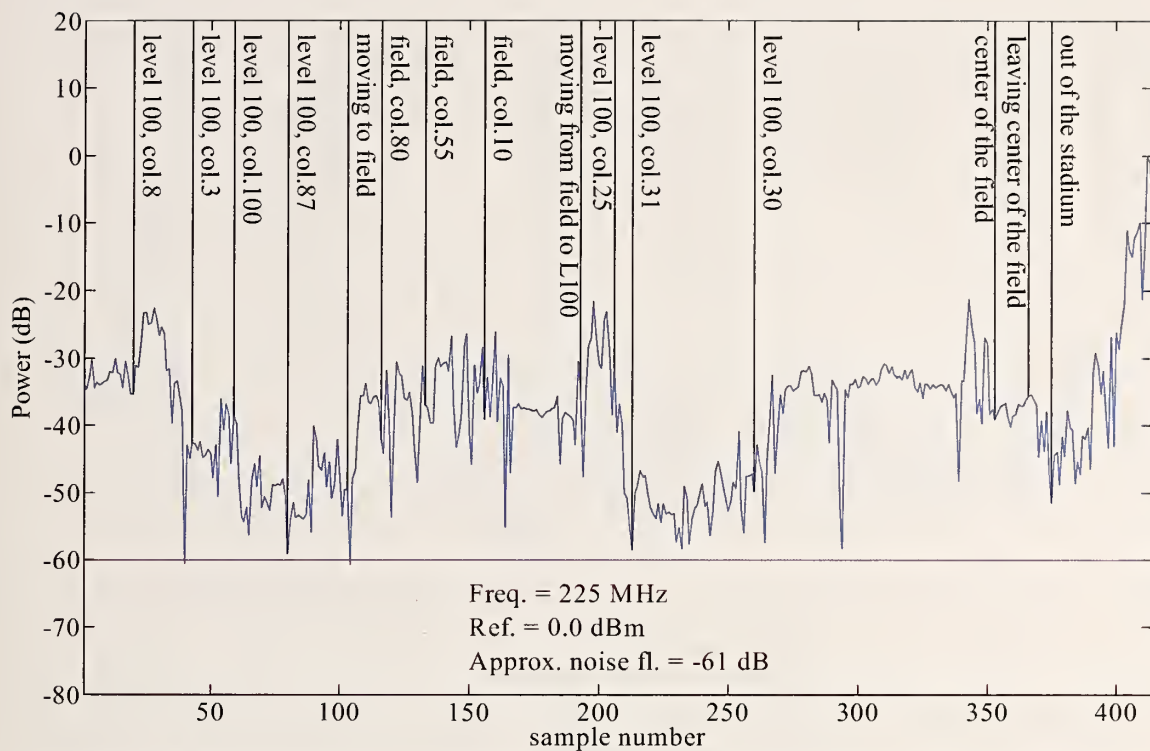


Figure 64. Philadelphia, PA sports stadium second inside walk at 225.30 MHz; horizontal polarization.

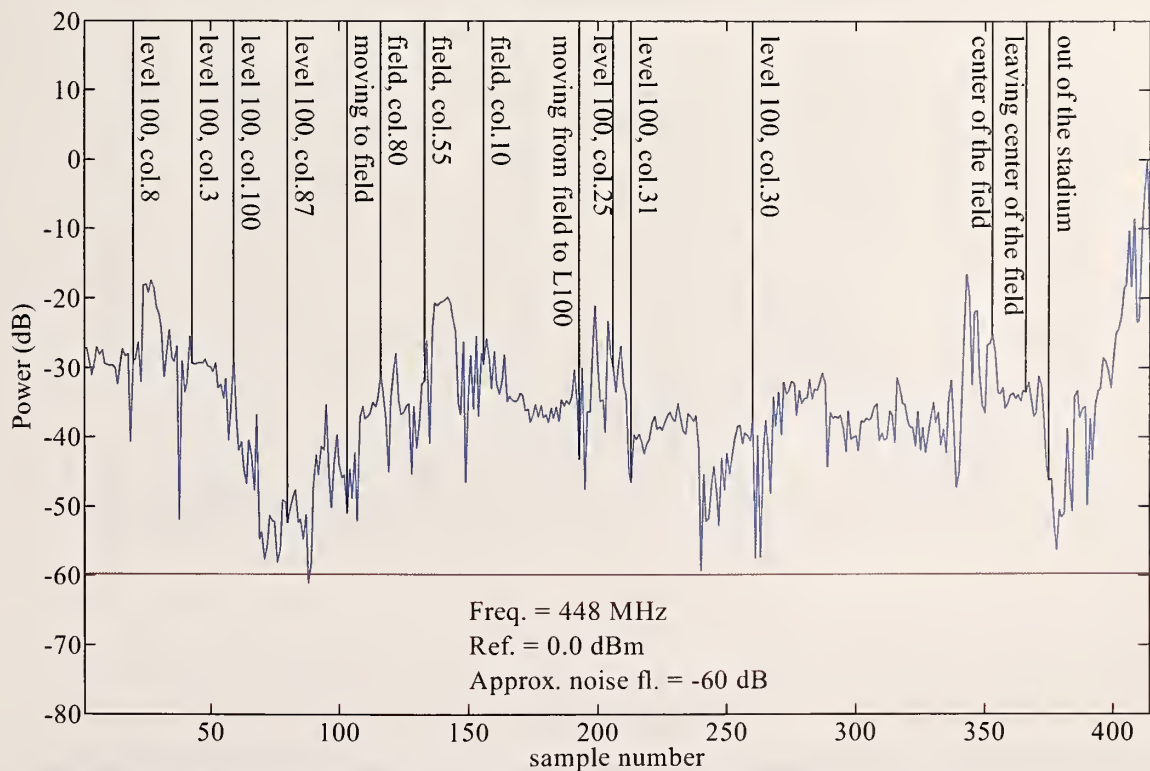


Figure 65. Philadelphia, PA sports stadium second inside walk at 448.50 MHz; horizontal polarization.

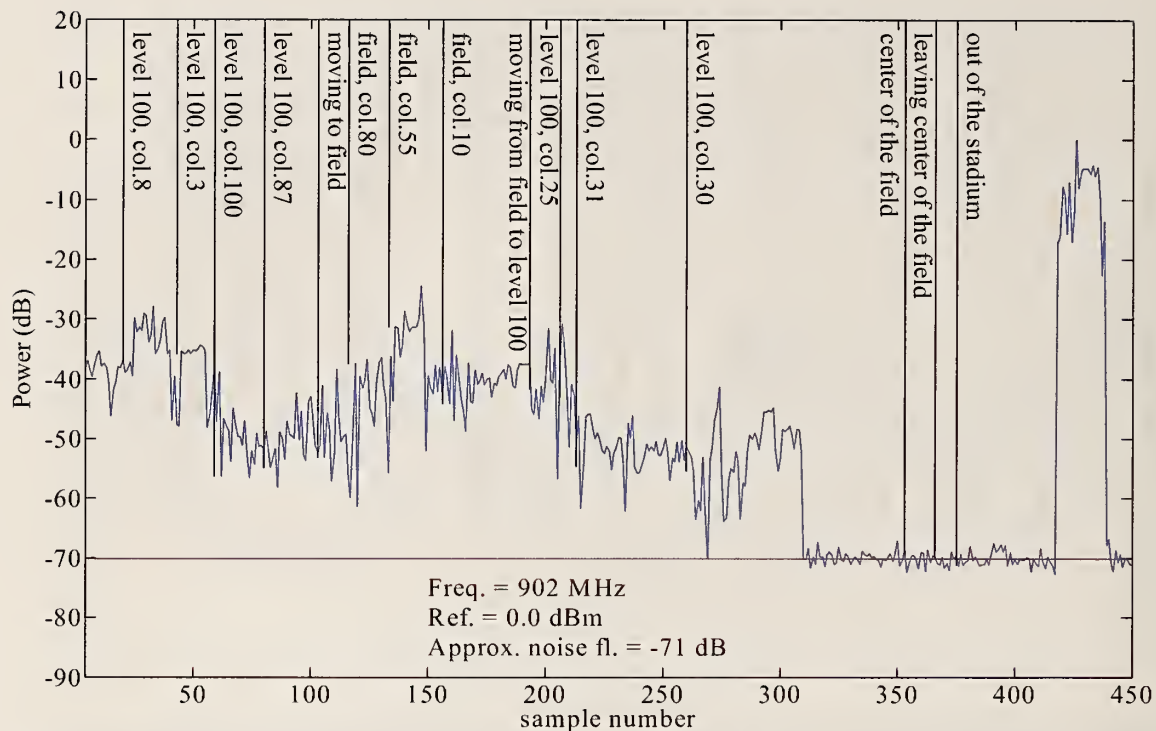


Figure 66. Philadelphia, PA sports stadium second inside walk at 902.45 MHz; horizontal polarization.

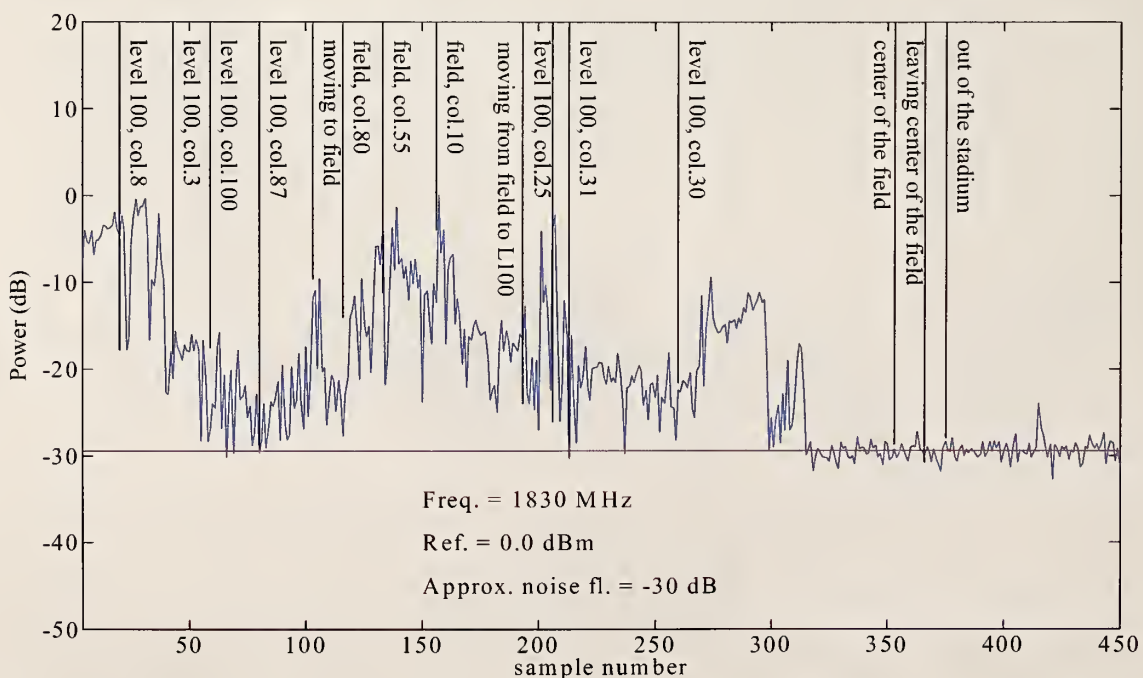


Figure 67. Philadelphia, PA sports stadium second inside walk at 1832.00 MHz; horizontal polarization.

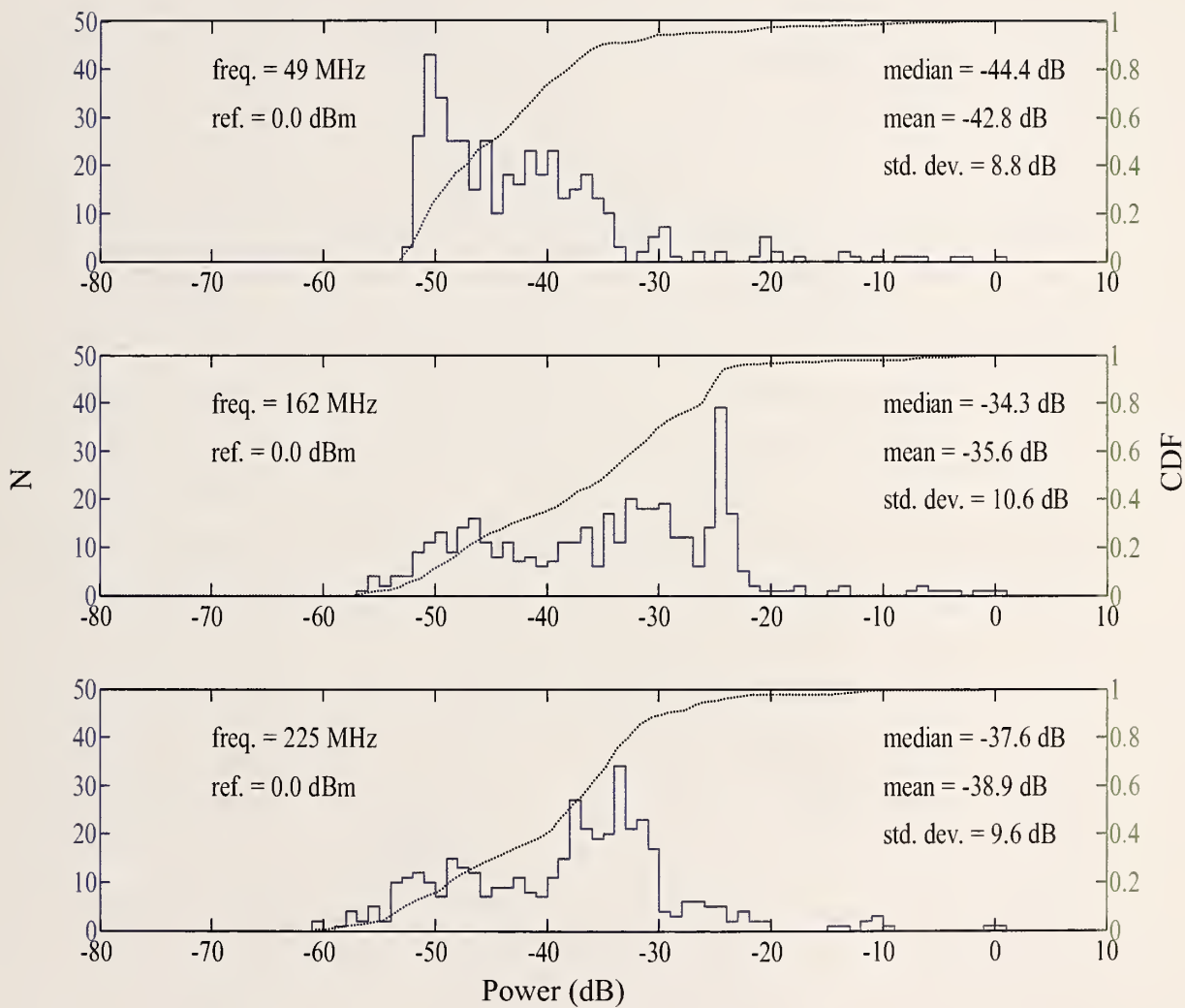


Figure 68. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for second inside walk data at 49.60, 162.09, and 225.30 MHz; horizontal polarization.



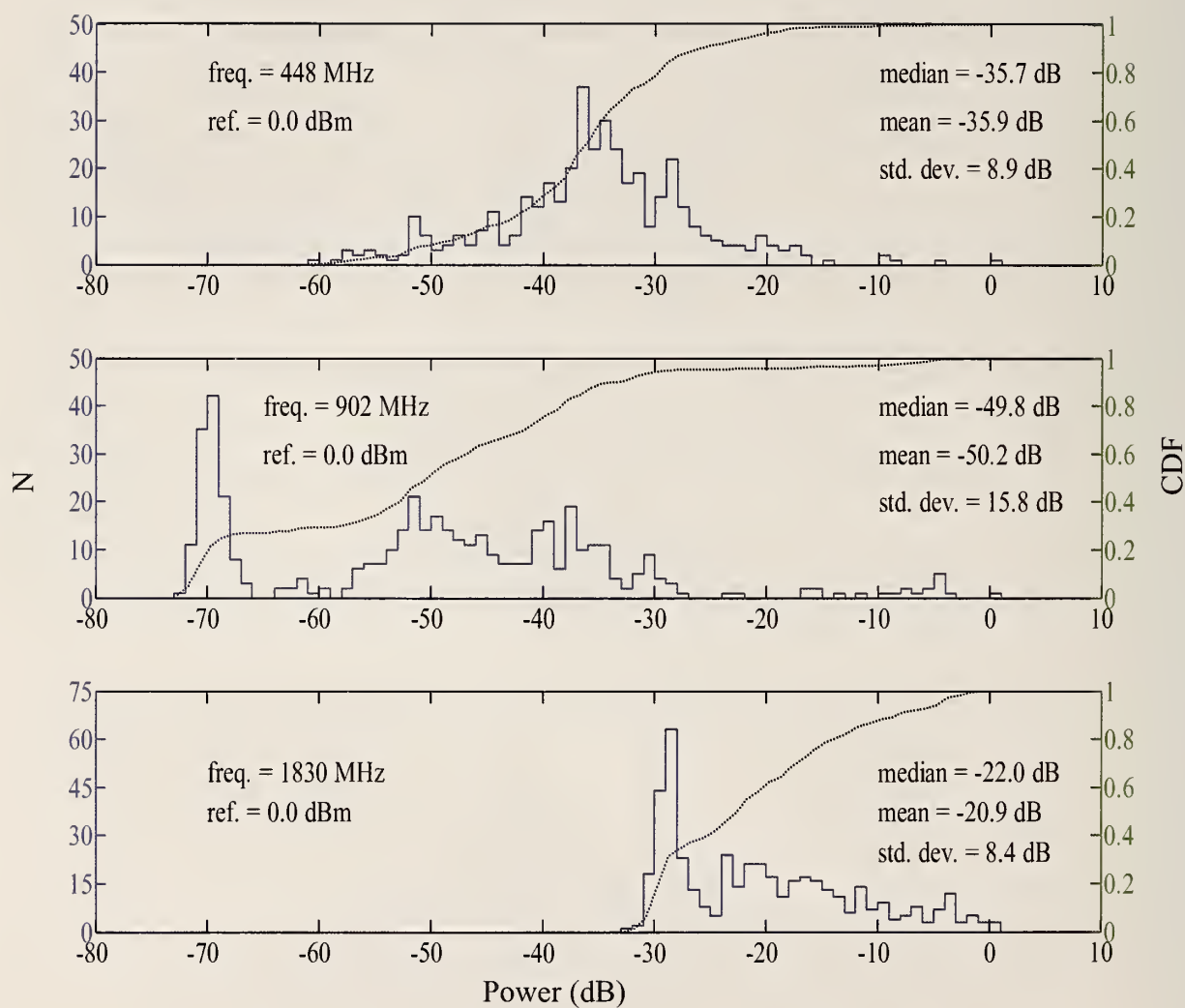


Figure 69. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for second inside walk data at 448.50, 902.45, and 1832.00 MHz; horizontal polarization.

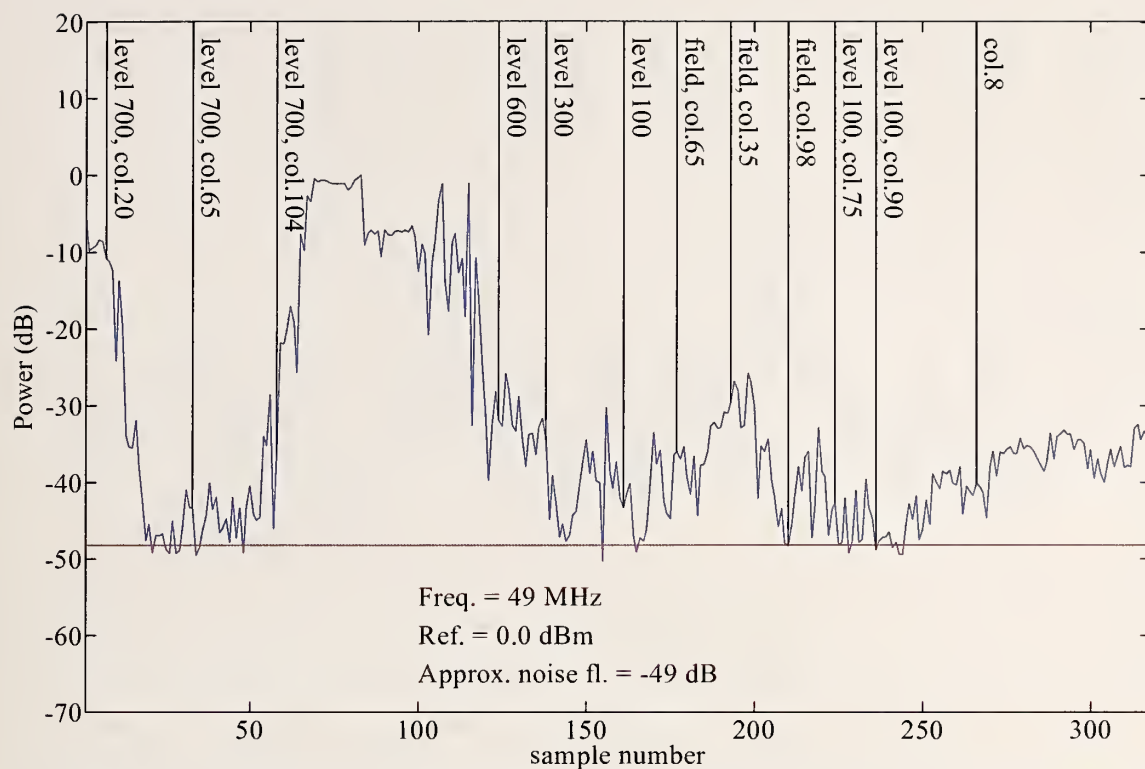


Figure 70. Philadelphia, PA sports stadium inside walk at 49.60 MHz; vertical polarization.

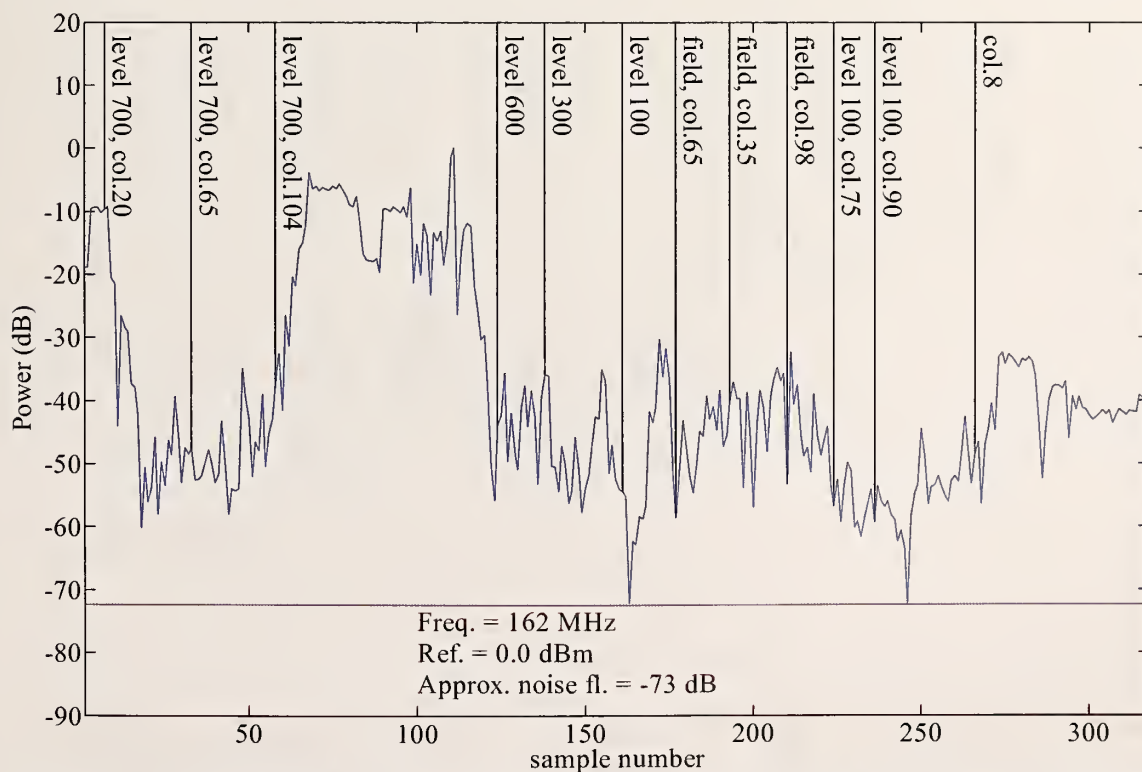


Figure 71. Philadelphia, PA sports stadium inside walk at 162.09 MHz; vertical polarization.

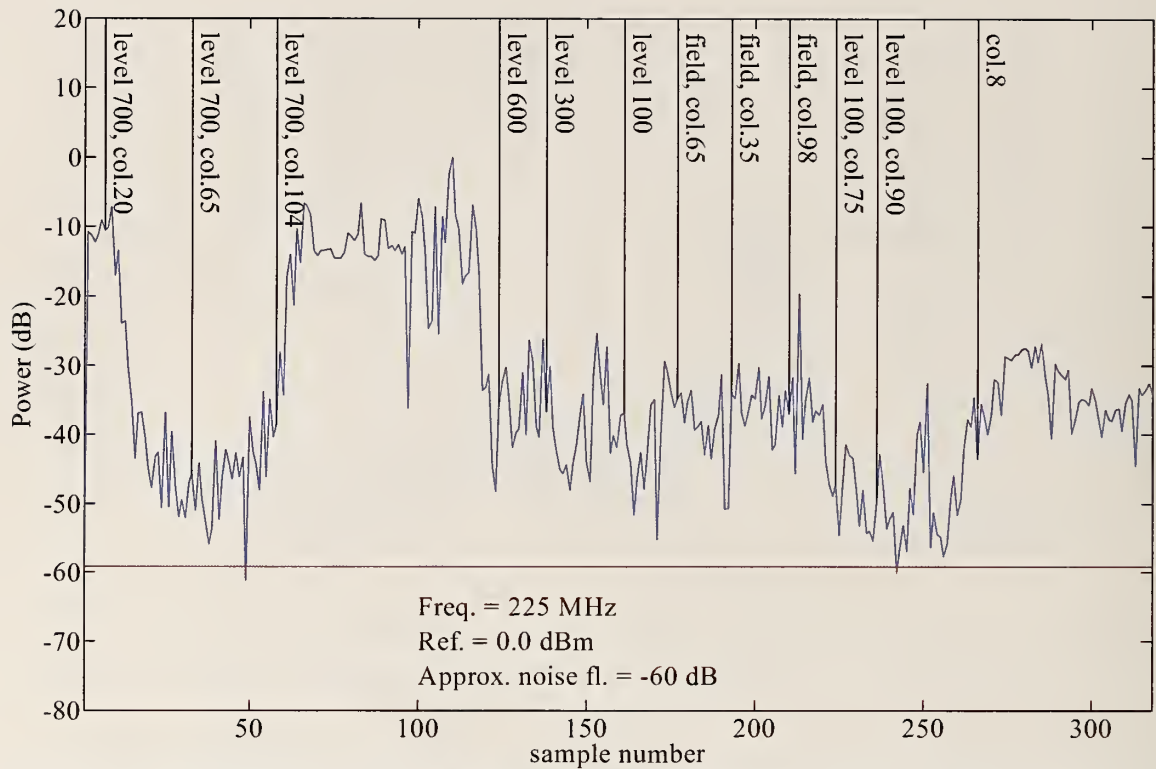


Figure 72. Philadelphia, PA sports stadium inside walk at 225.30 MHz; vertical polarization.

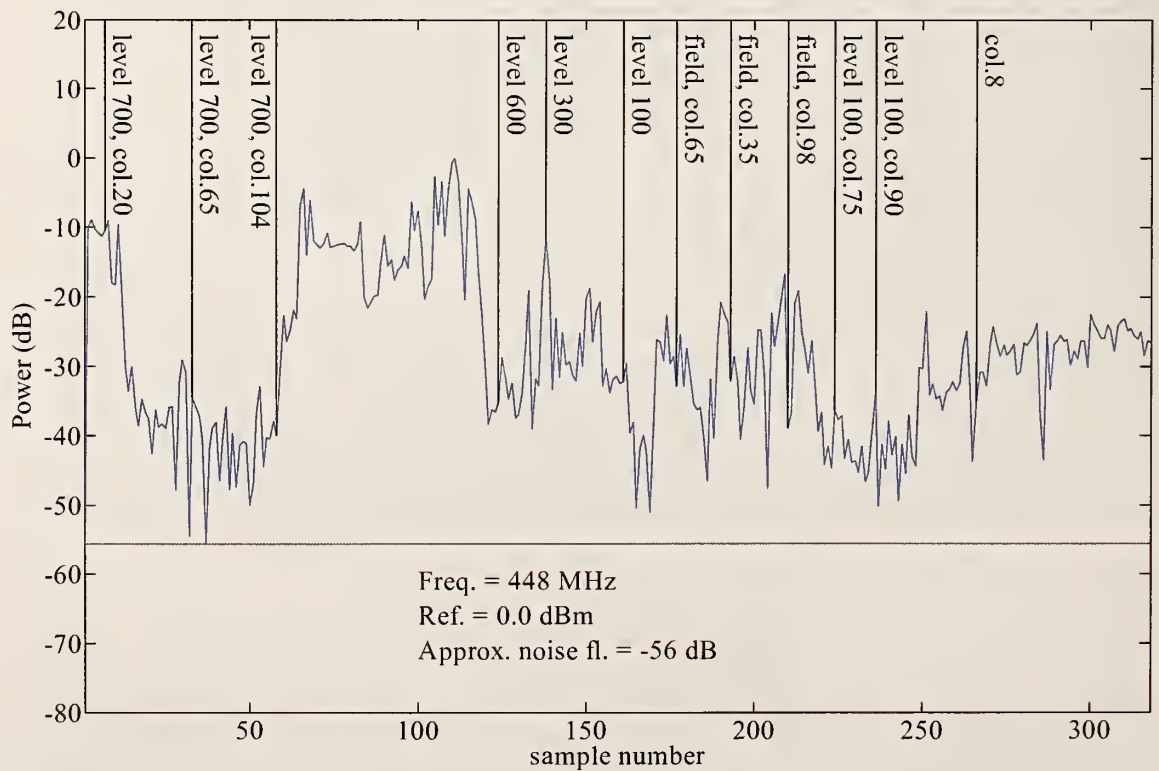


Figure 73. Philadelphia, PA sports stadium inside walk at 448.50 MHz; vertical polarization.



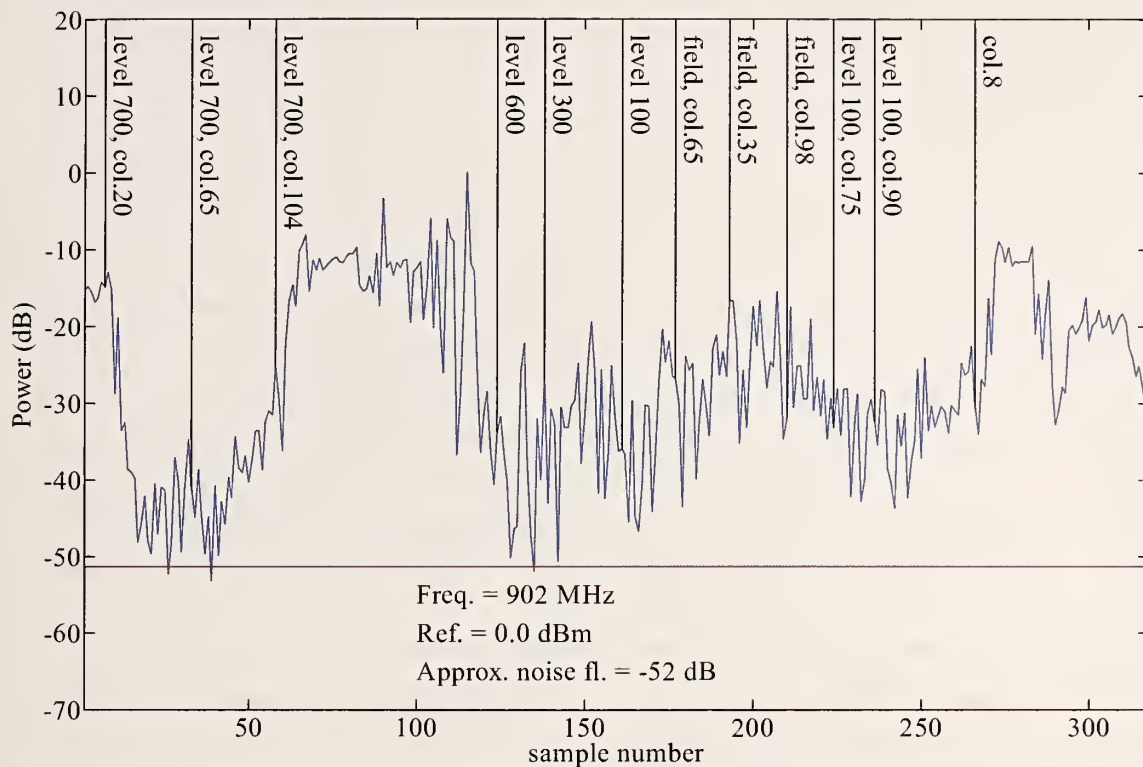


Figure 74. Philadelphia, PA sports stadium inside walk at 902.45 MHz; vertical polarization.

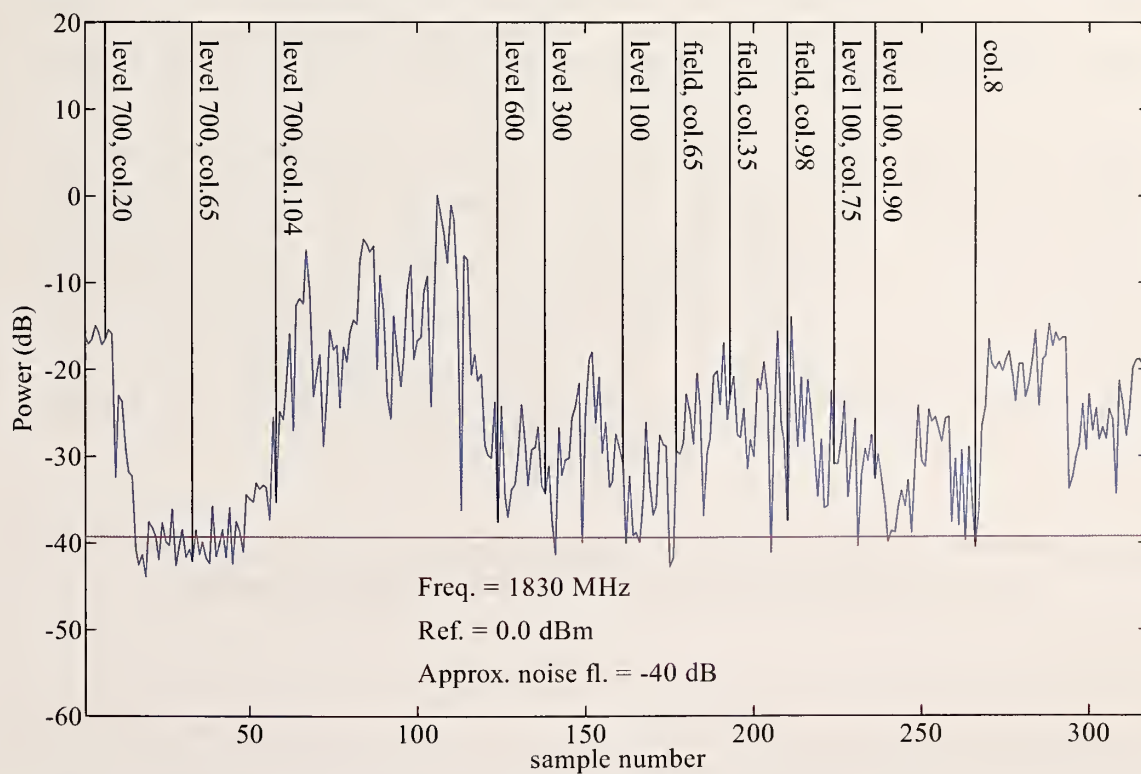


Figure 75. Philadelphia, PA sports stadium inside walk at 1832.00 MHz; vertical polarization.

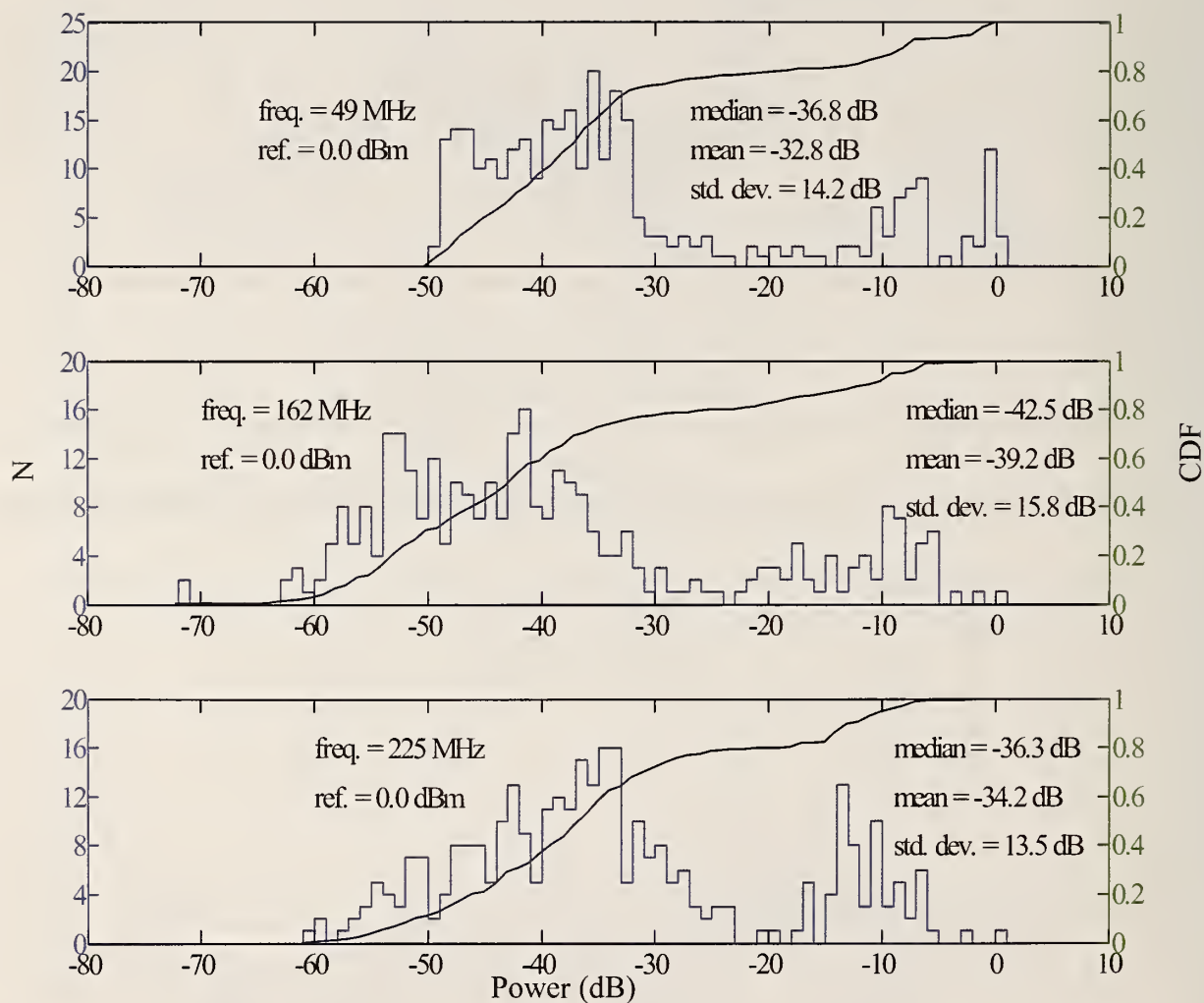


Figure 76. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for inside walk data at 49.60, 162.09, and 225.30 MHz; vertical polarization.

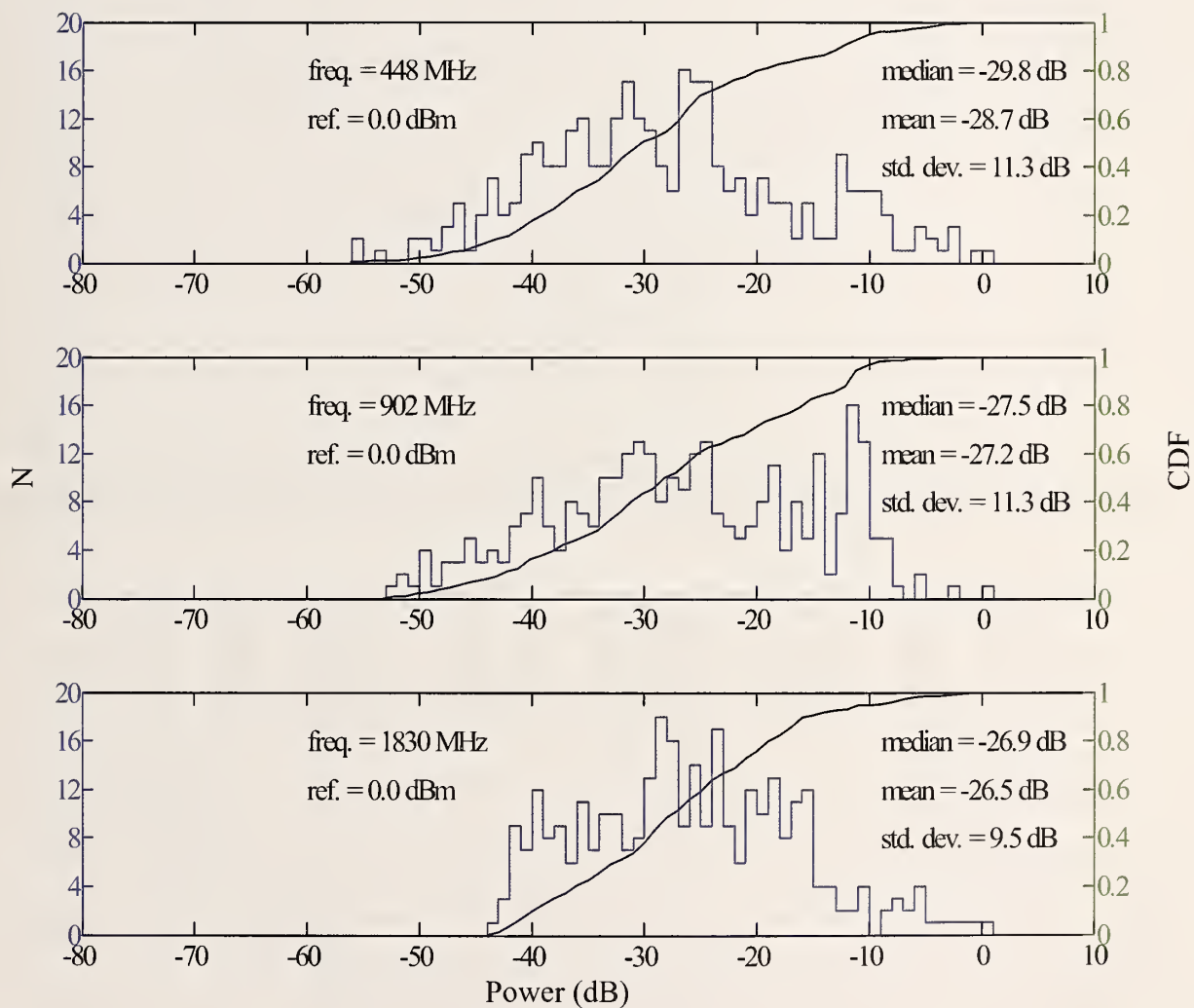


Figure 77. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for inside walk data at 448.50, 902.45, and 1832.00 MHz; vertical polarization.



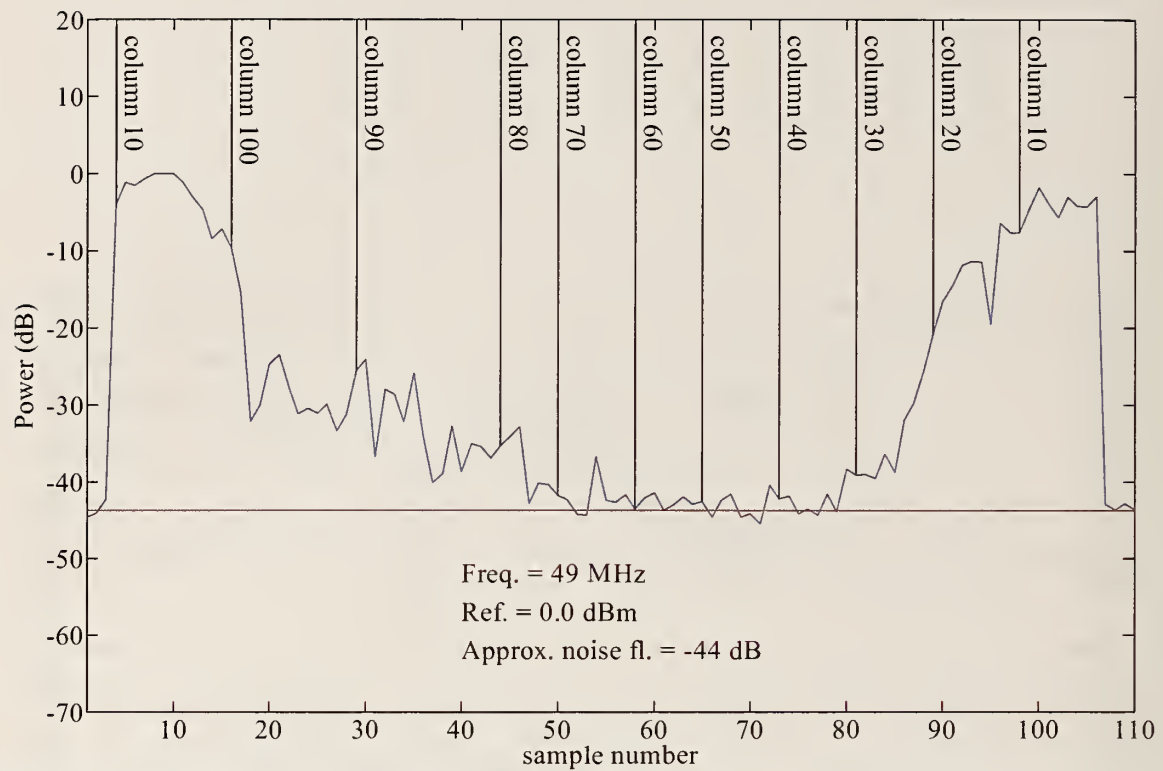


Figure 78. Philadelphia, PA sports stadium outside walk at 49.60 MHz; horizontal polarization.

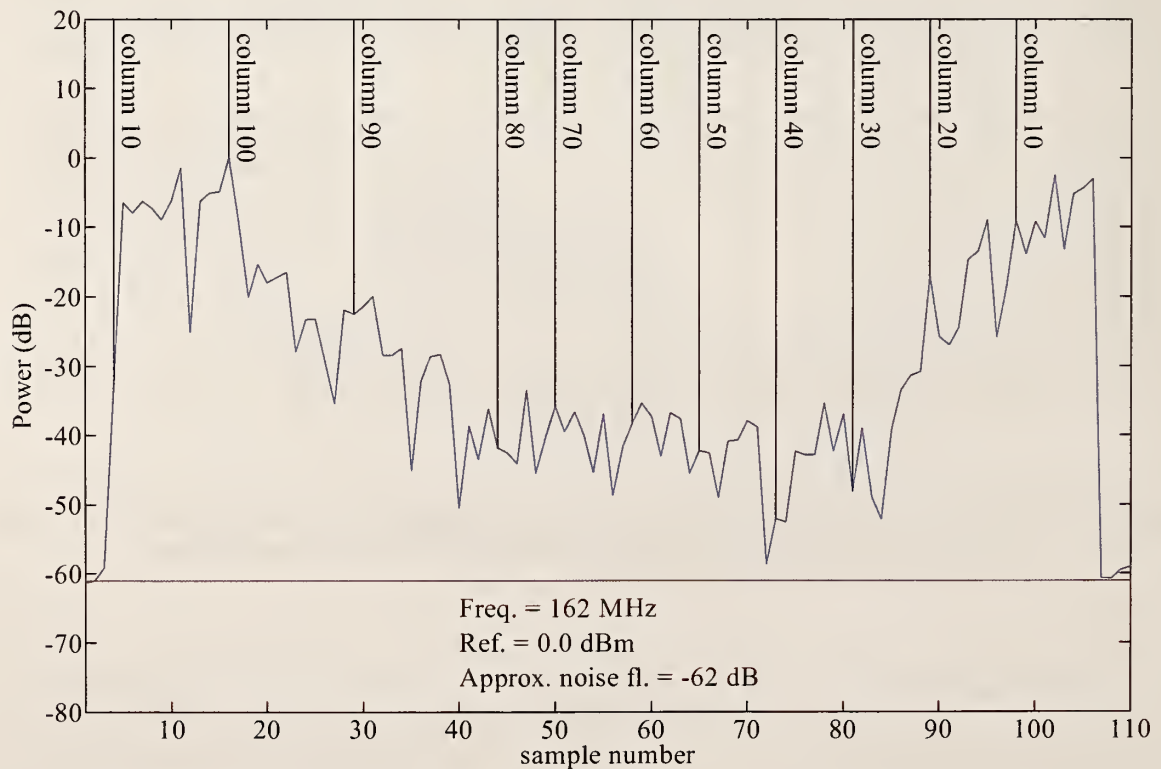


Figure 79. Philadelphia, PA sports stadium outside walk at 162.09 MHz; horizontal polarization.

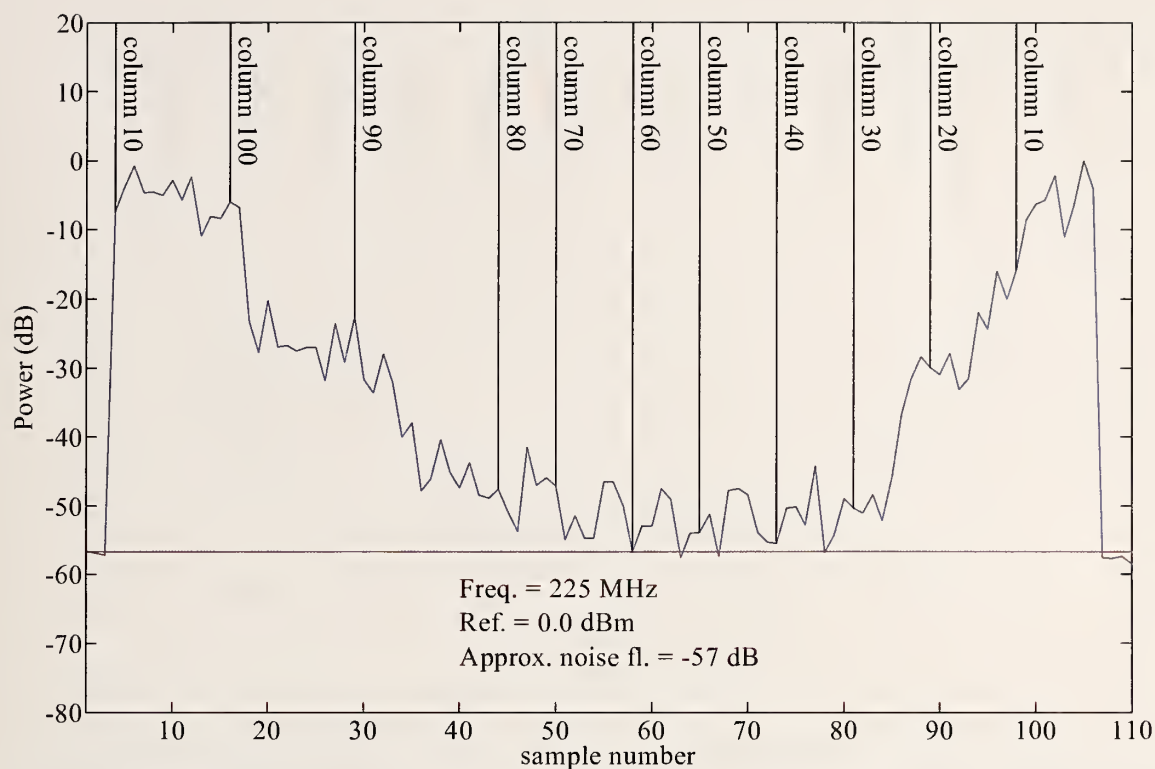


Figure 80. Philadelphia, PA sports stadium outside walk at 225.30 MHz; horizontal polarization.

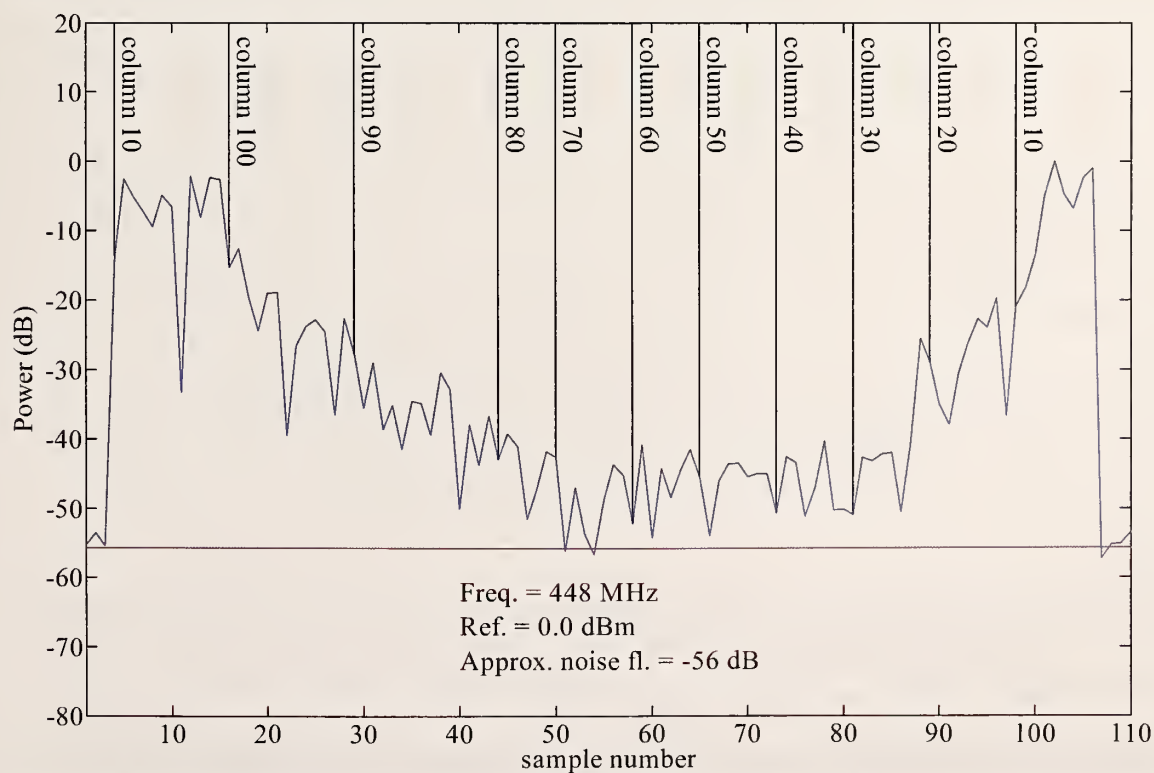


Figure 81. Philadelphia, PA sports stadium outside walk at 448.50 MHz; horizontal polarization.

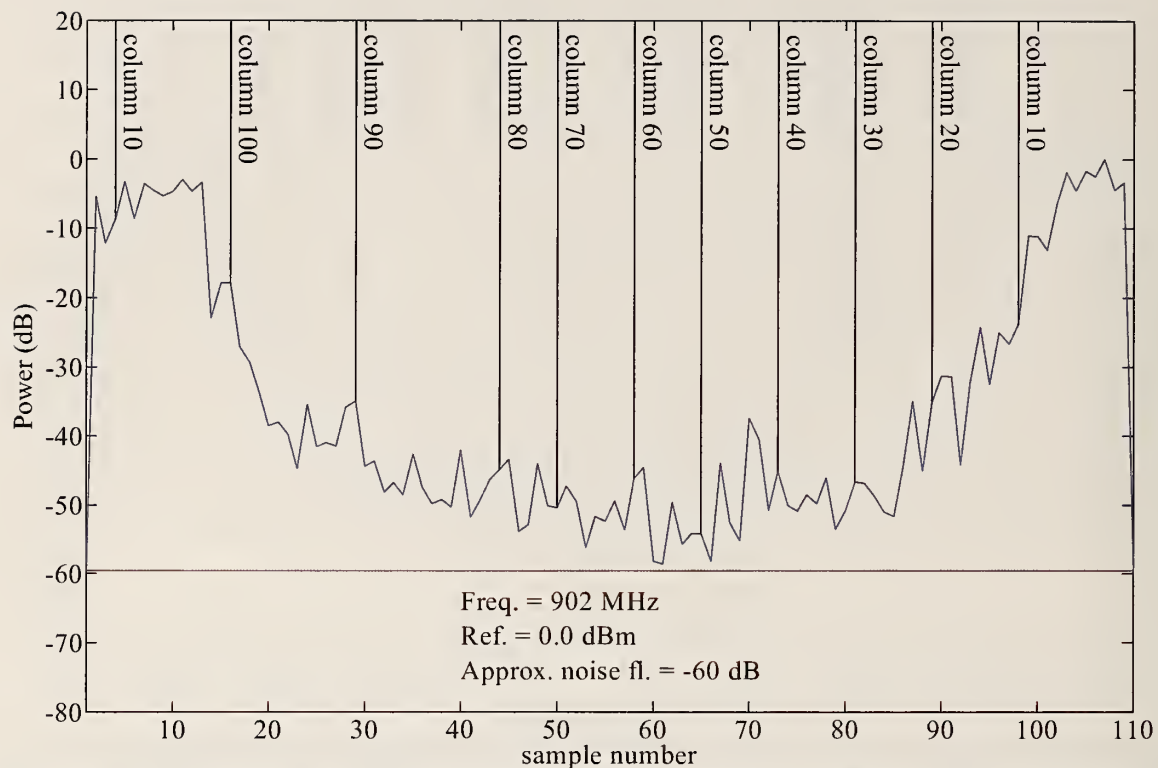


Figure 82. Philadelphia, PA sports stadium outside walk at 902.45 MHz; horizontal polarization.

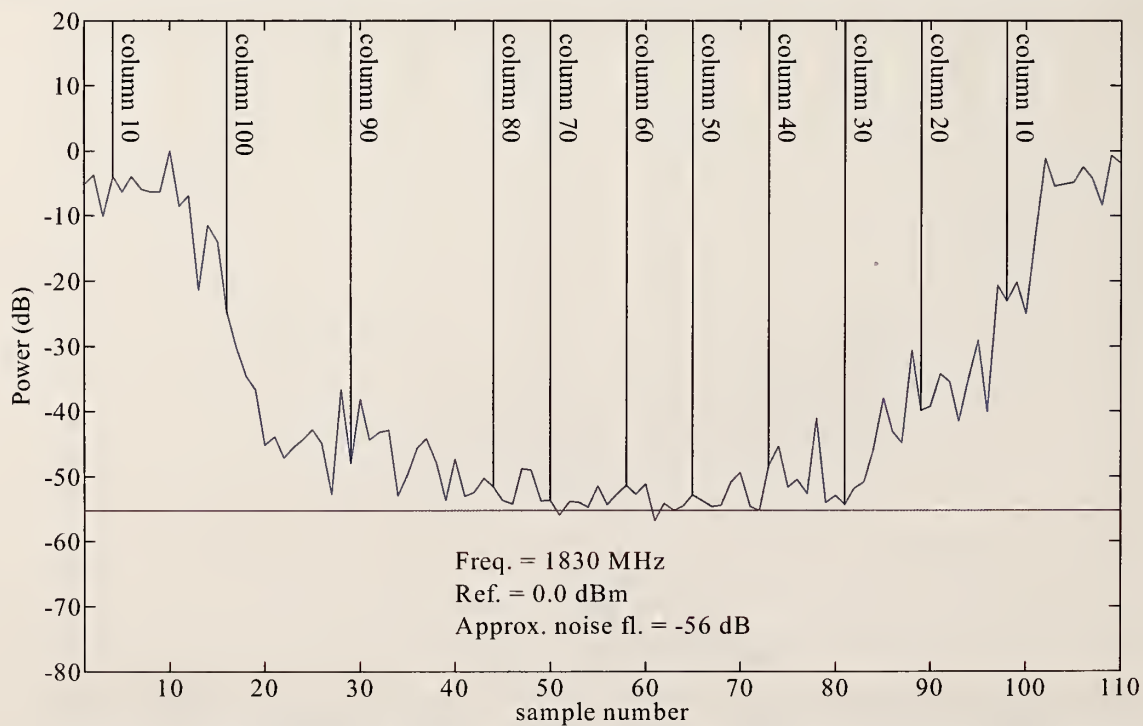


Figure 83. Philadelphia, PA sports stadium outside walk at 1832.00 MHz; horizontal polarization.



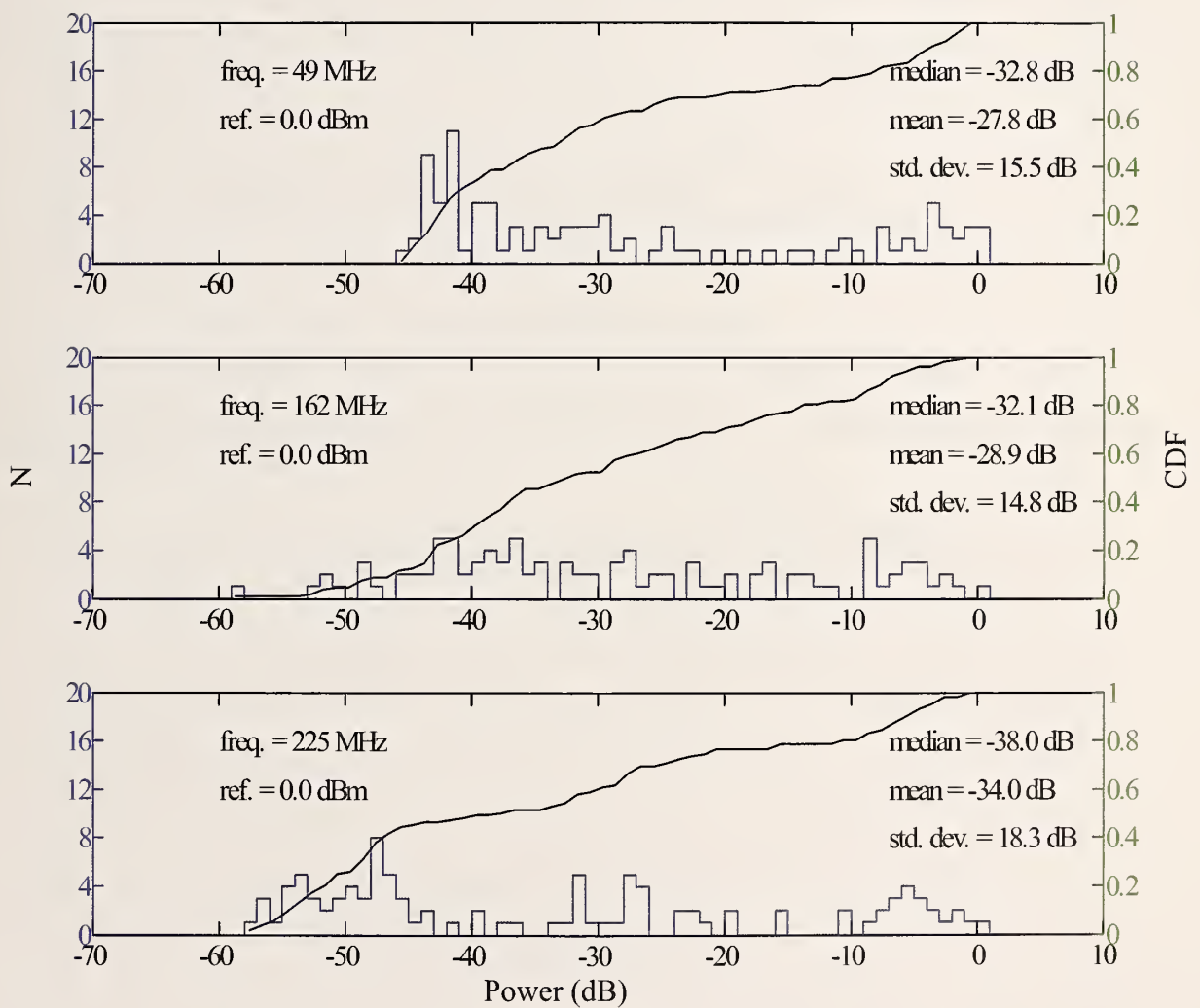


Figure 84. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for outside walk data at 49.60, 162.09, and 225.30 MHz; horizontal polarization.

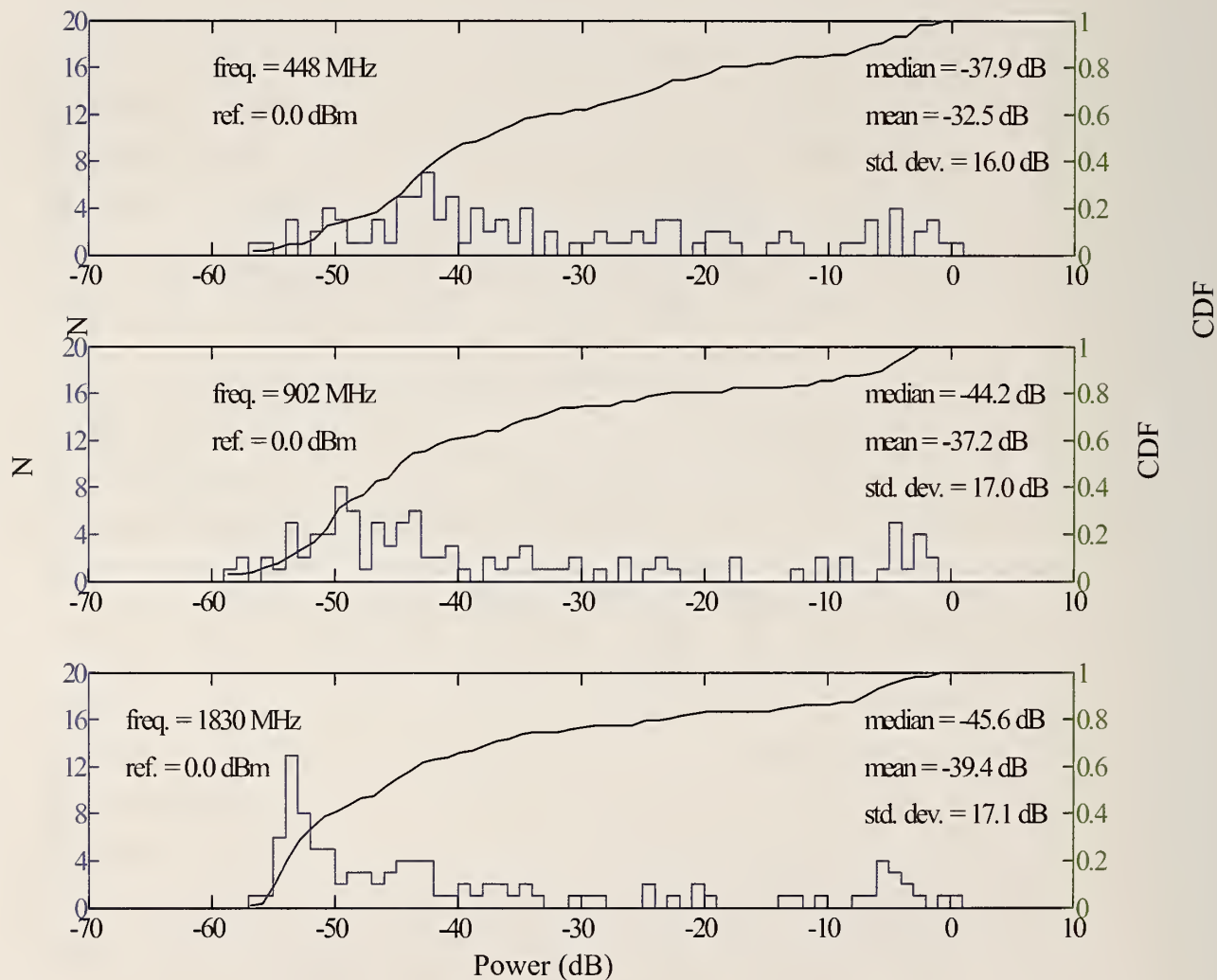


Figure 85. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for outside walk data at 448.50, 902.45, and 1832.00 MHz; horizontal polarization

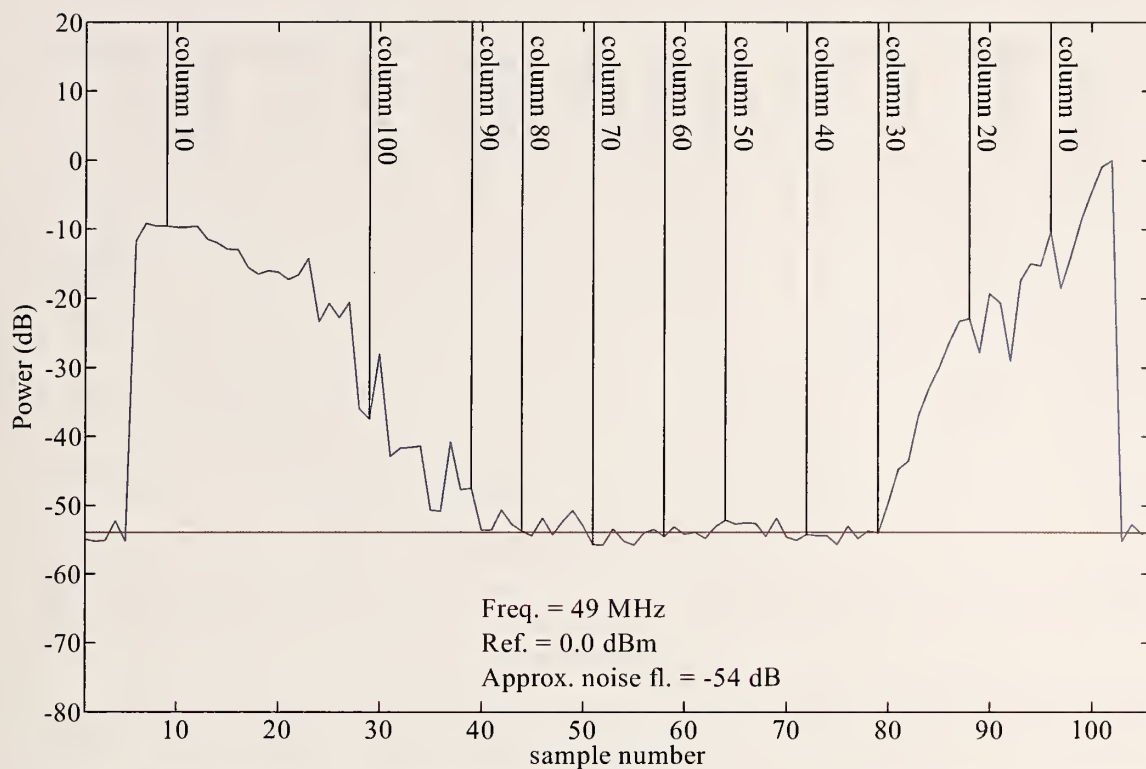


Figure 86. Philadelphia, PA sports stadium outside walk at 49.60 MHz; vertical polarization.

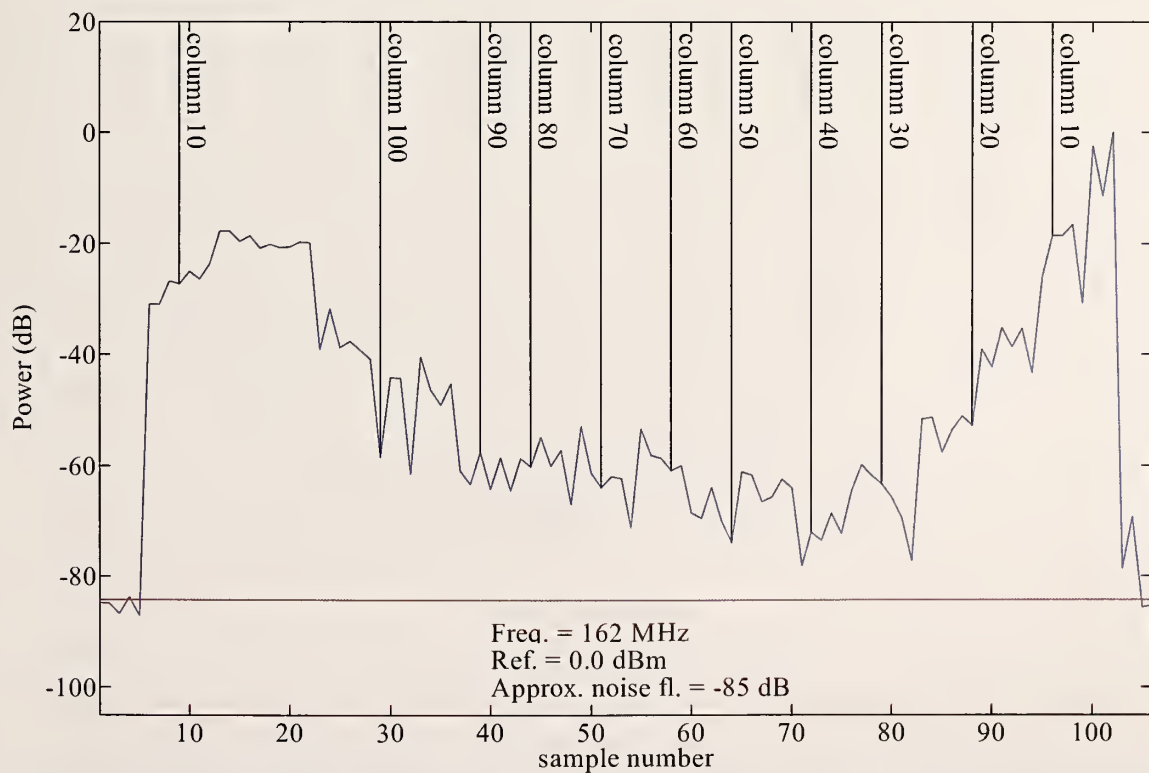


Figure 87. Philadelphia, PA sports stadium outside walk at 162.09 MHz; vertical polarization.



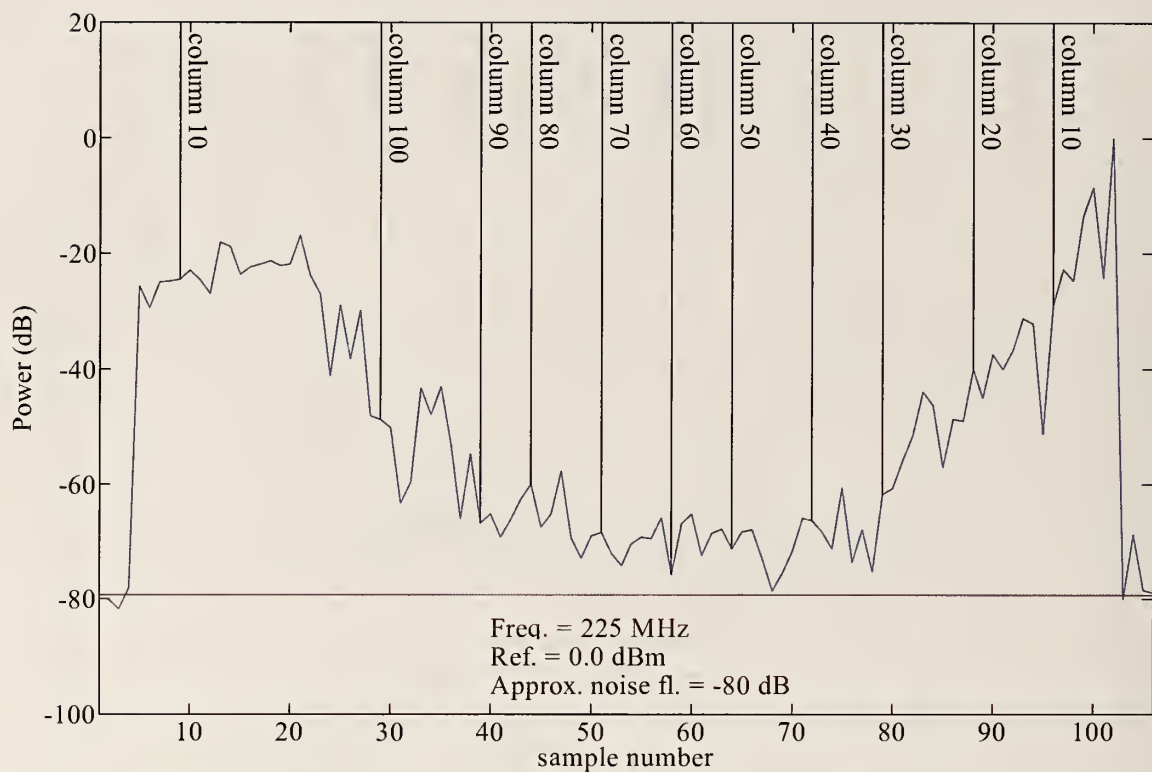


Figure 88. Philadelphia, PA sports stadium outside walk at 225.30 MHz; vertical polarization.

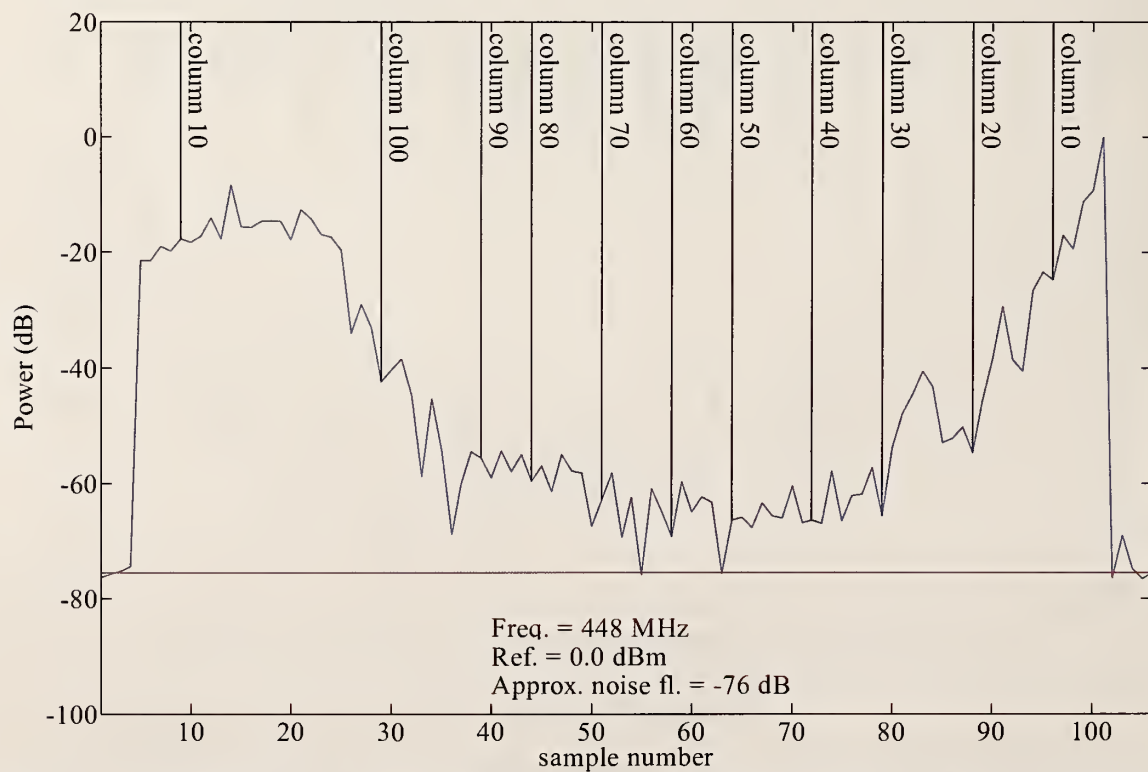


Figure 89. Philadelphia, PA sports stadium outside walk at 448.50 MHz; vertical polarization.

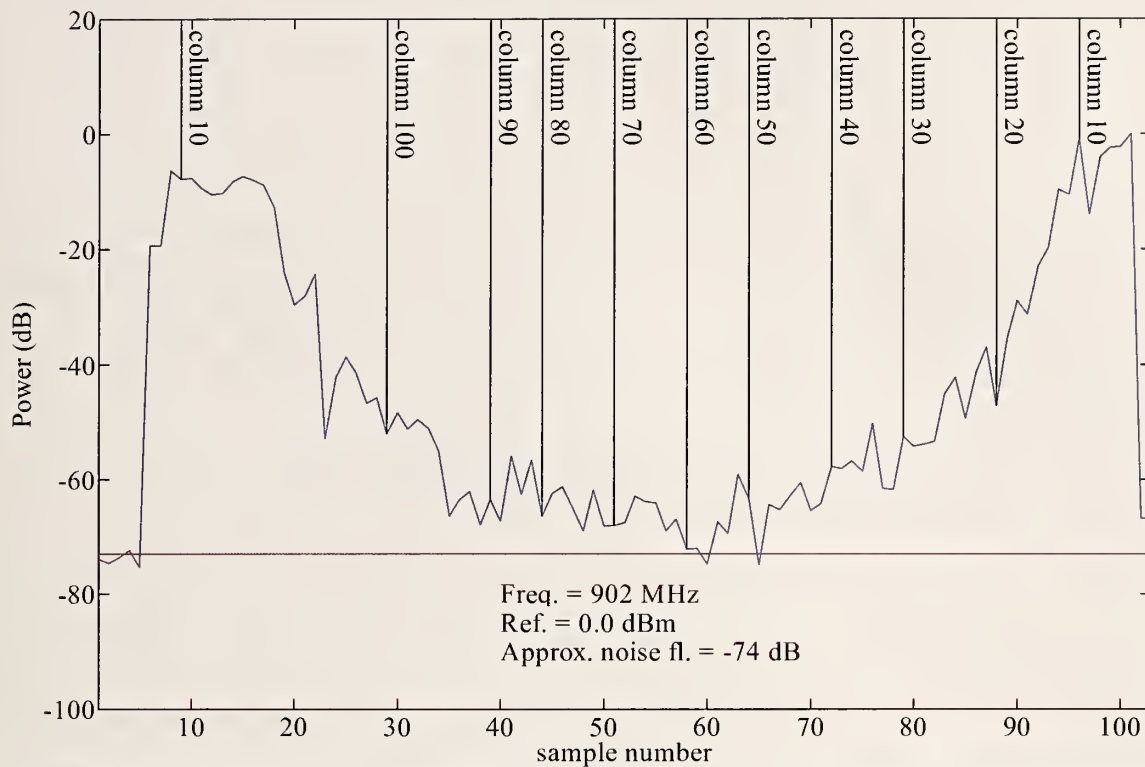


Figure 90. Philadelphia, PA sports stadium outside walk at 902.45 MHz; vertical polarization.

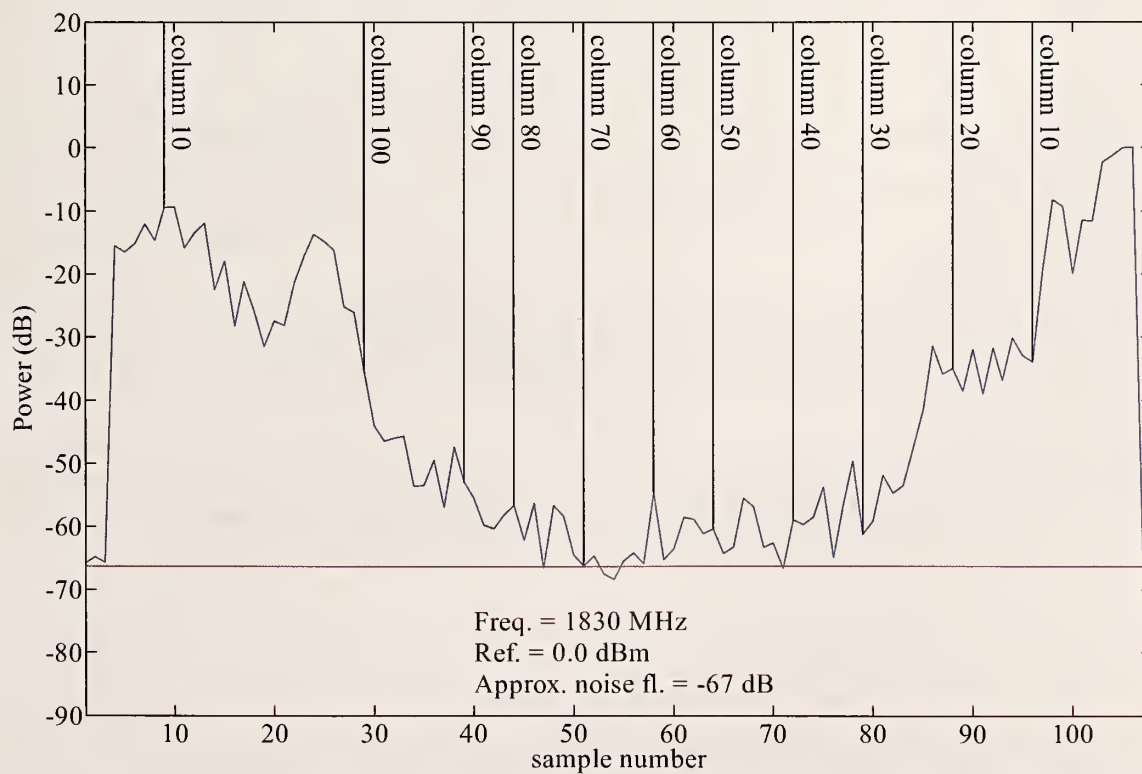


Figure 91. Philadelphia, PA sports stadium outside walk at 1832.00 MHz; vertical polarization.

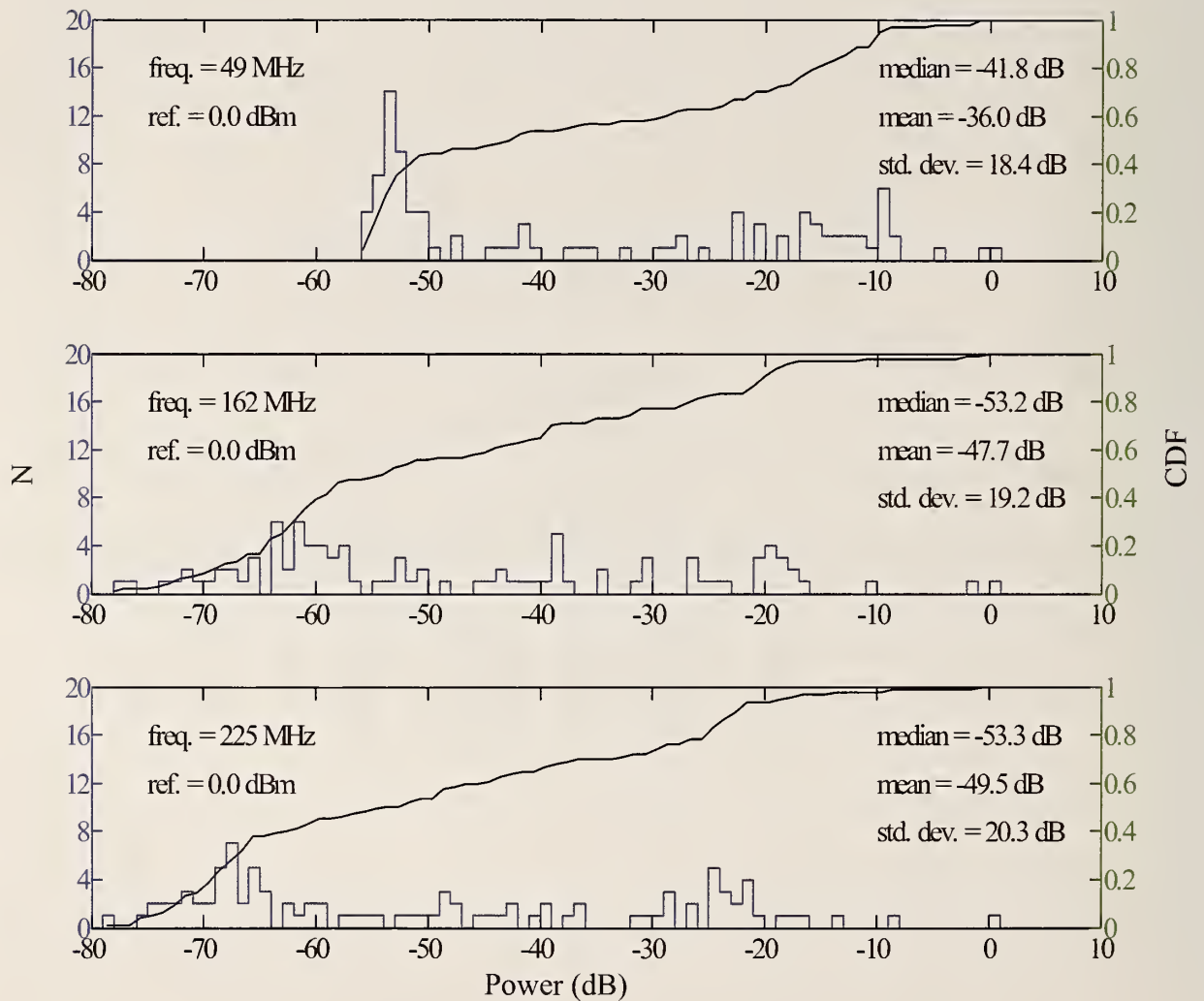


Figure 92. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for outside walk data at 49.60, 162.09, and 225.30 MHz; vertical polarization.



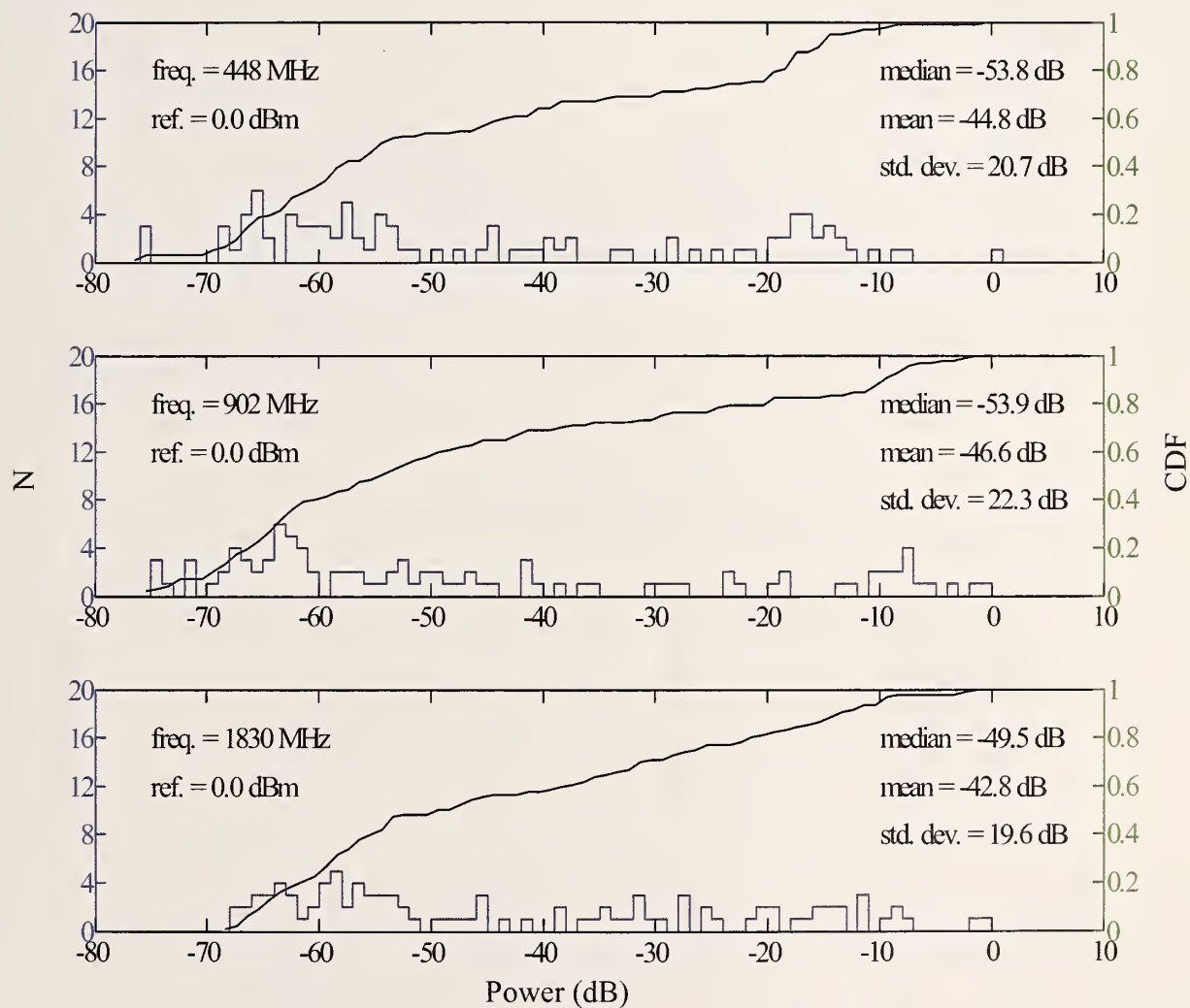


Figure 93. Philadelphia, PA sports stadium statistics, histograms, and empirical CDF for outside walk data at 448.50, 902.45, and 1832.00 MHz; vertical polarization

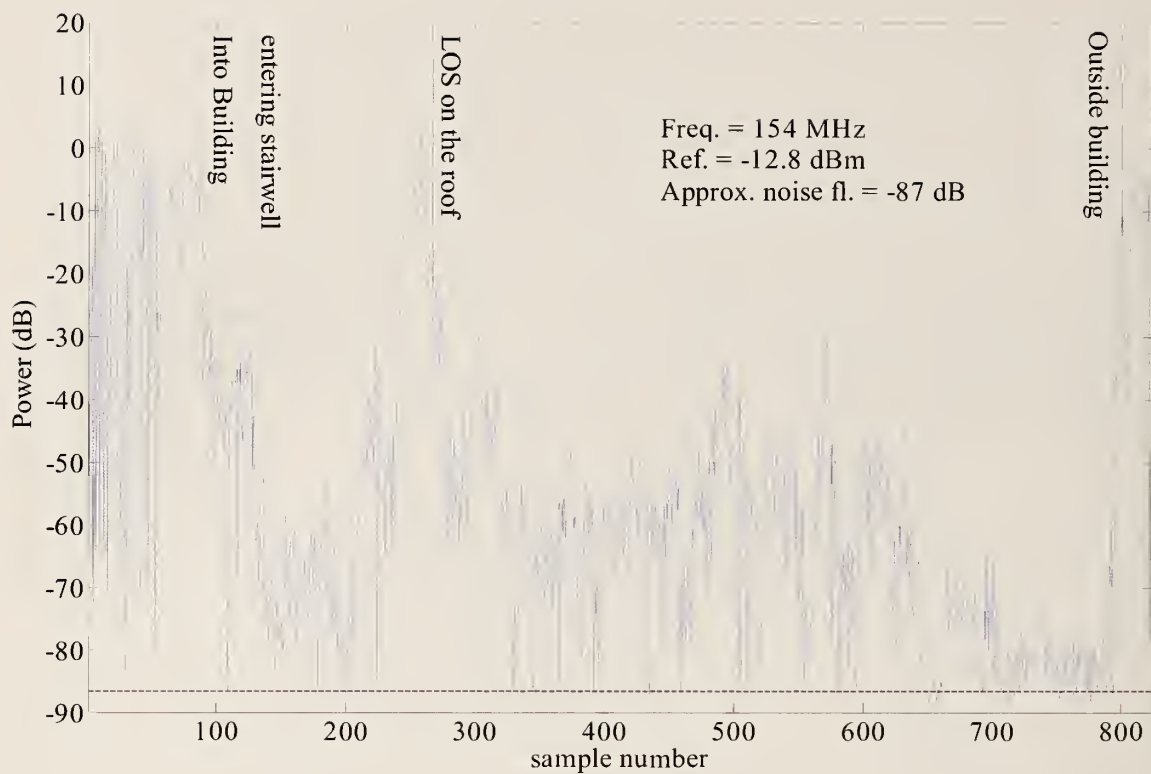


Figure 94. Phoenix, AZ office building walk-through at 154.07 MHz.

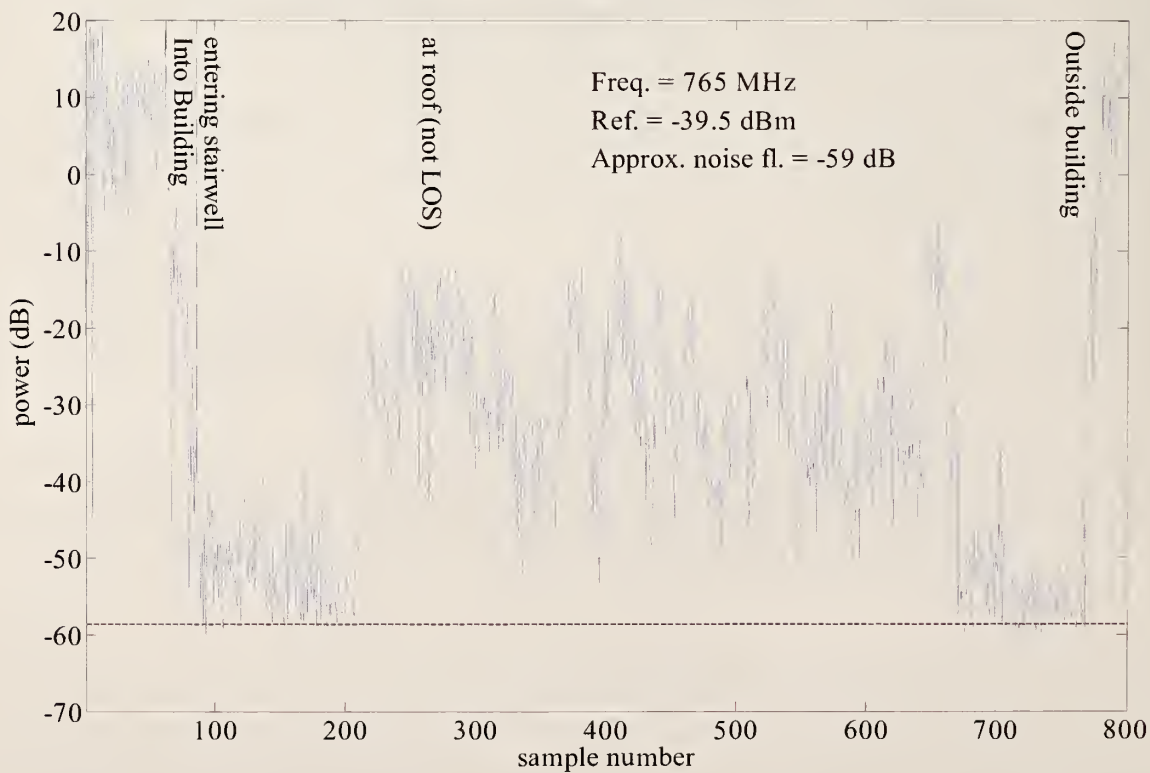


Figure 95. Phoenix, AZ office building walk-through at 765 MHz.

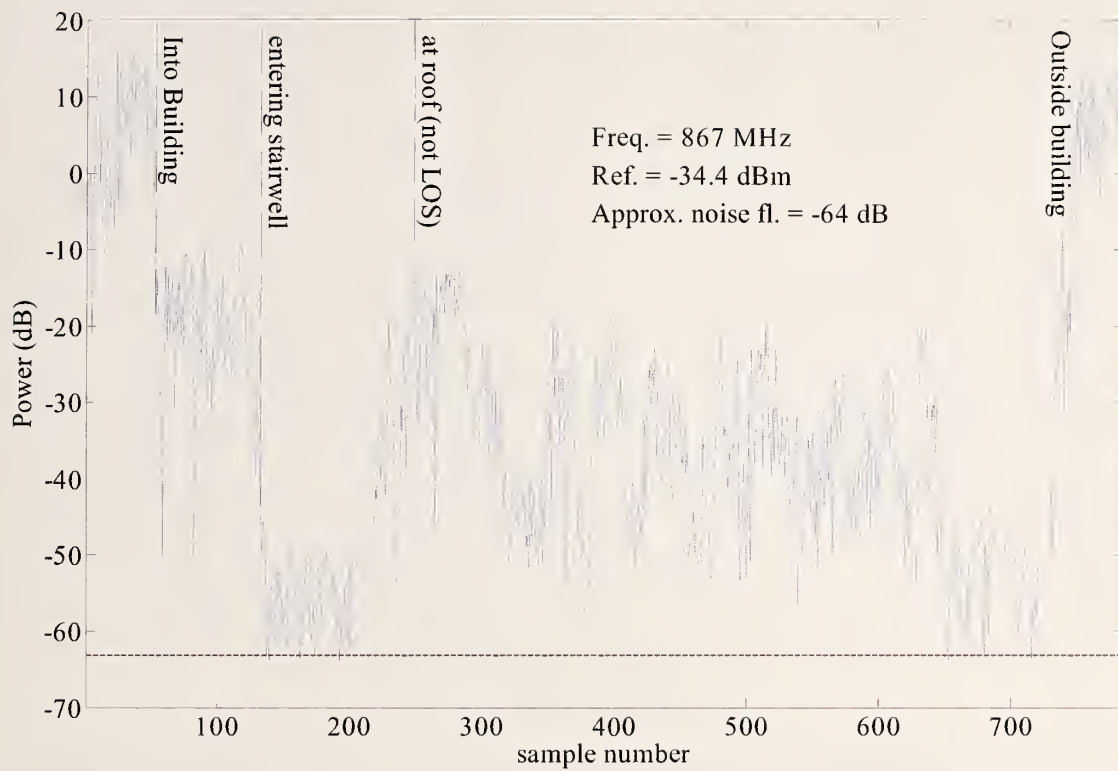


Figure 96. Phoenix, AZ office building walk-through at 867 MHz.



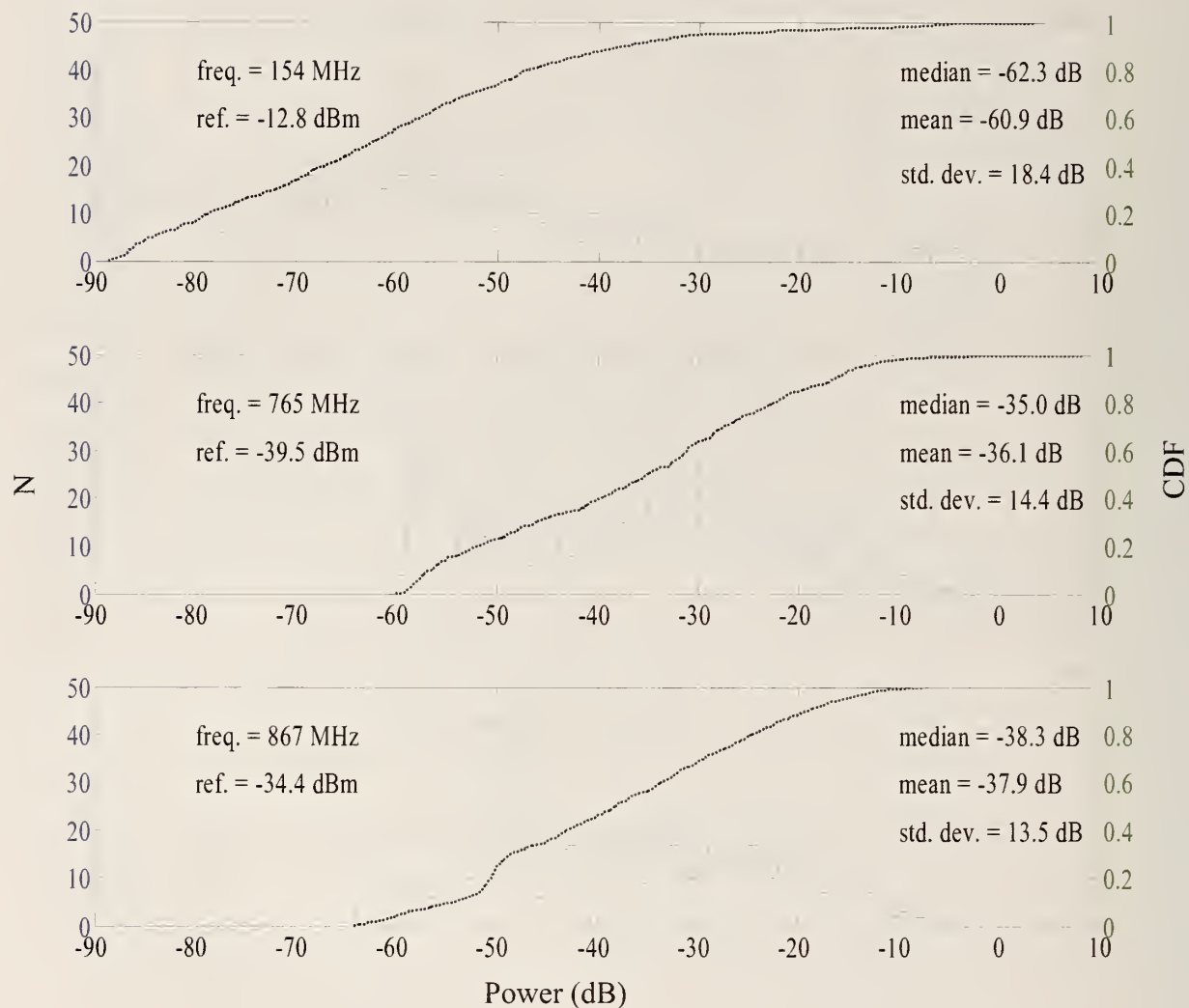


Figure 97. Phoenix, AZ office building statistics, histograms, and empirical CDF for walk-through data at 154, 765, and 867 MHz.

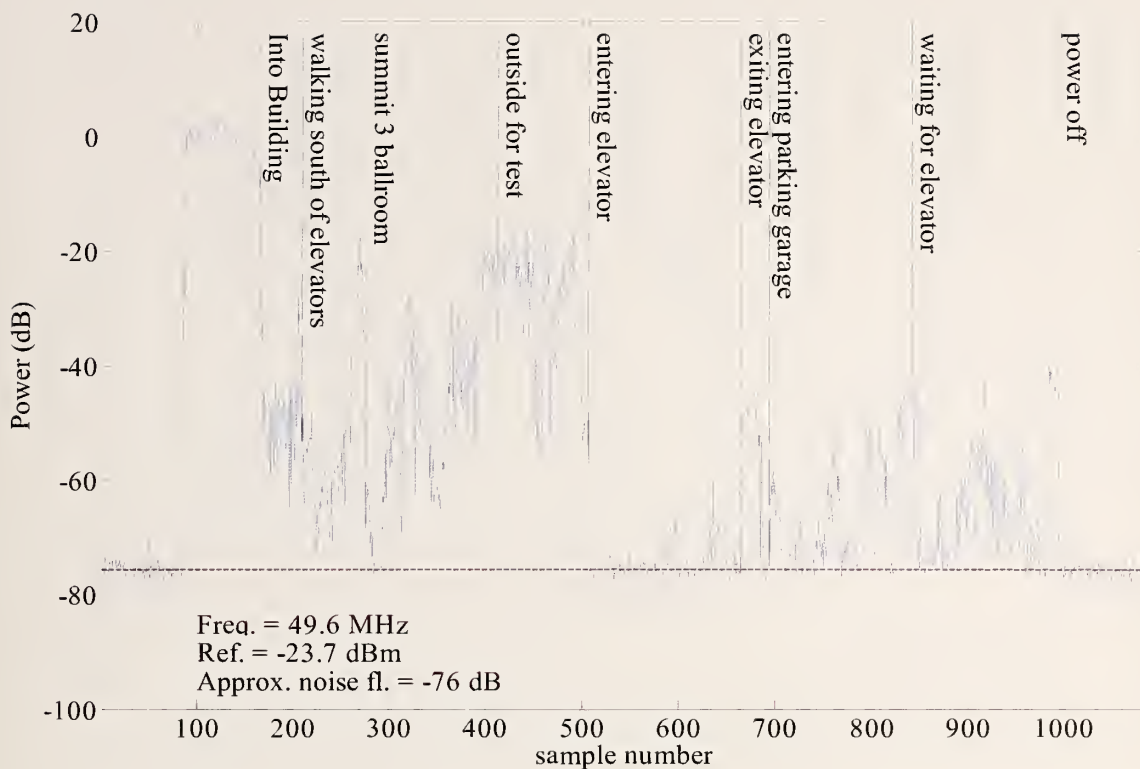


Figure 98. Colorado Springs, CO hotel first walk-through at 49.60 MHz; receiver at site 1.

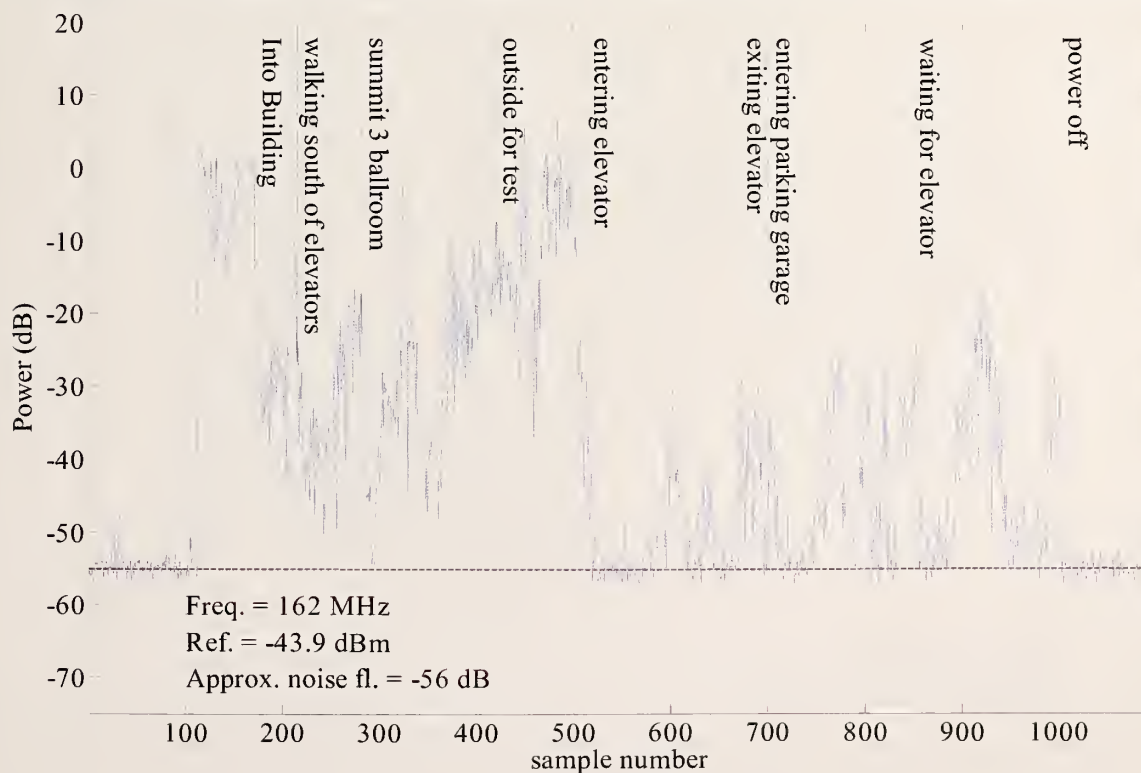


Figure 99. Colorado Springs, CO hotel first walk-through at 162.09 MHz; receiver at site 1.

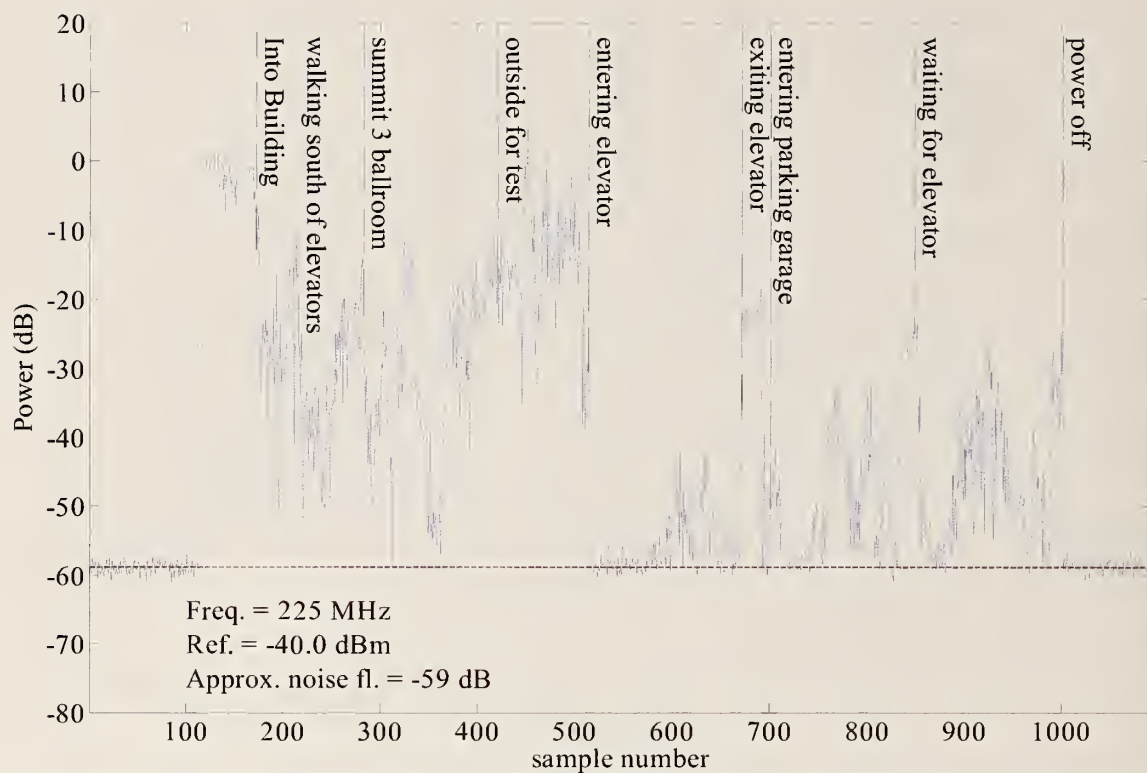


Figure 100. Colorado Springs, CO hotel first walk-through at 225.30 MHz; receiver at site 1

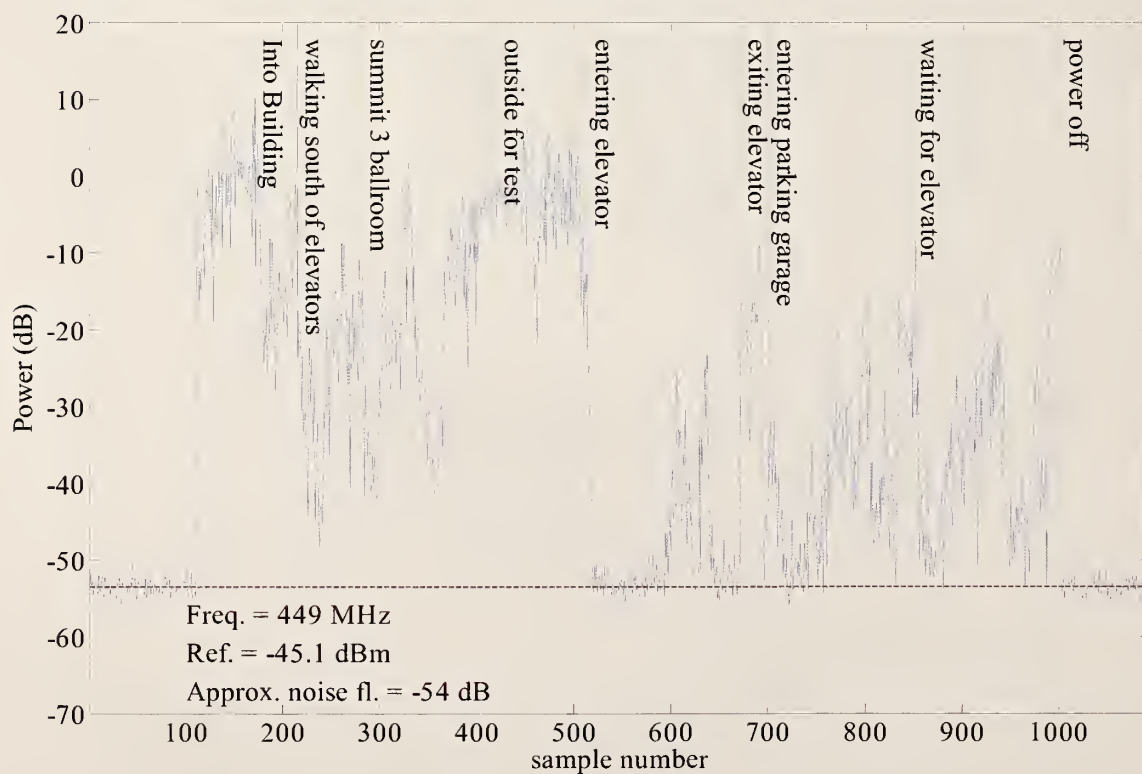


Figure 101. Colorado Springs, CO hotel first walk-through at 448.50 MHz; receiver at site 1.



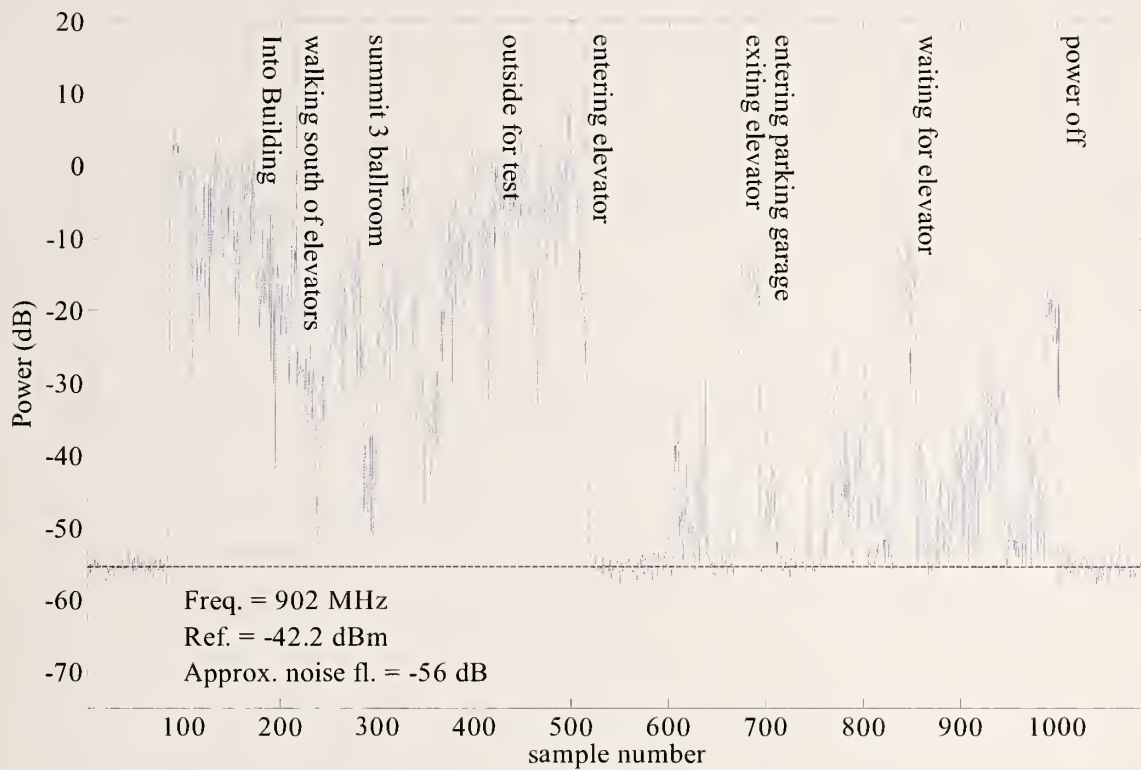


Figure 102. Colorado Springs, CO hotel first walk-through at 902.45 MHz; receiver at site 1.

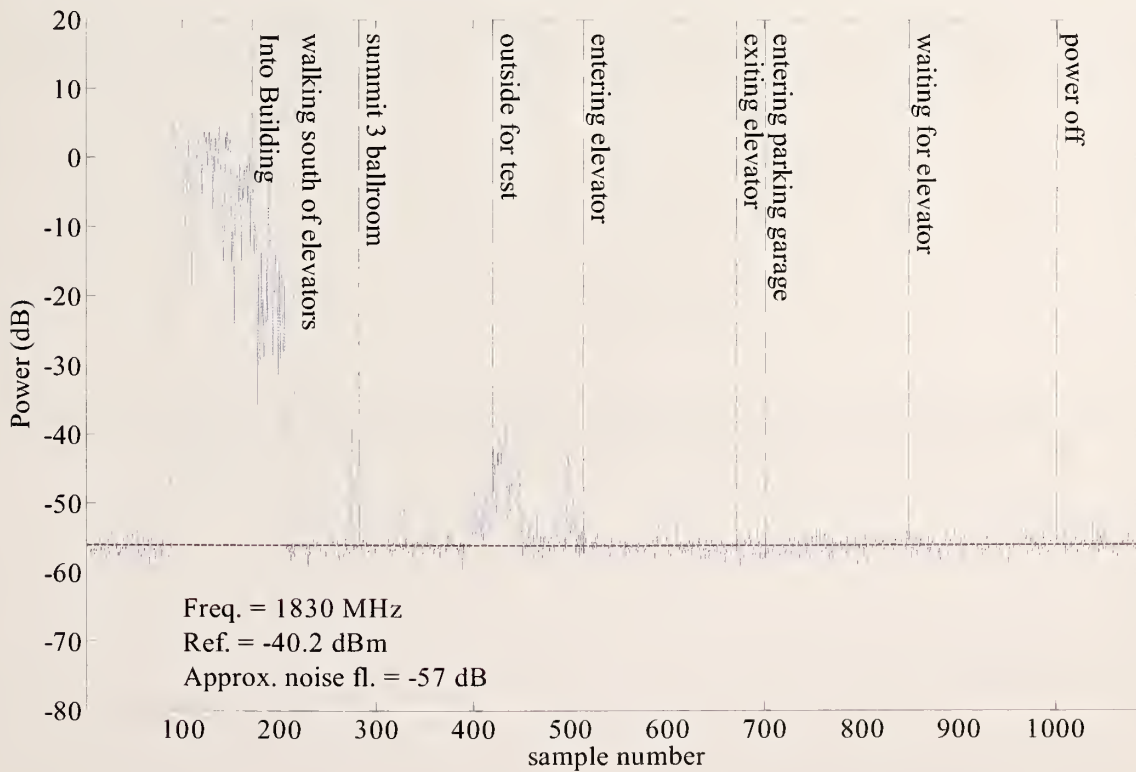


Figure 103. Colorado Springs, CO hotel first walk-through at 1830.00 MHz; receiver at site 1.

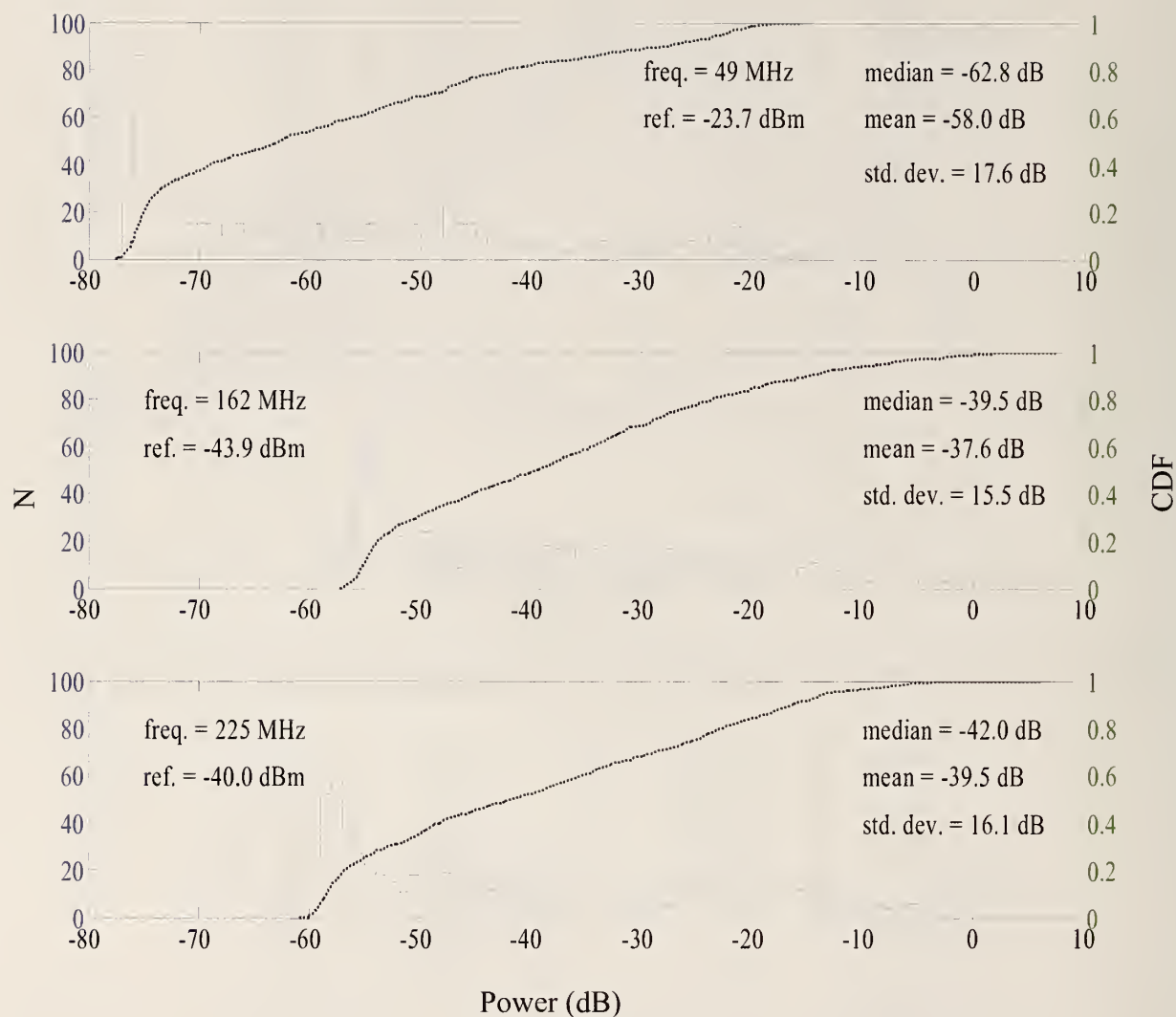


Figure 104. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for first walk-through data with the receiver at site 1; 49.60, 162.09, and 225.30 MHz.

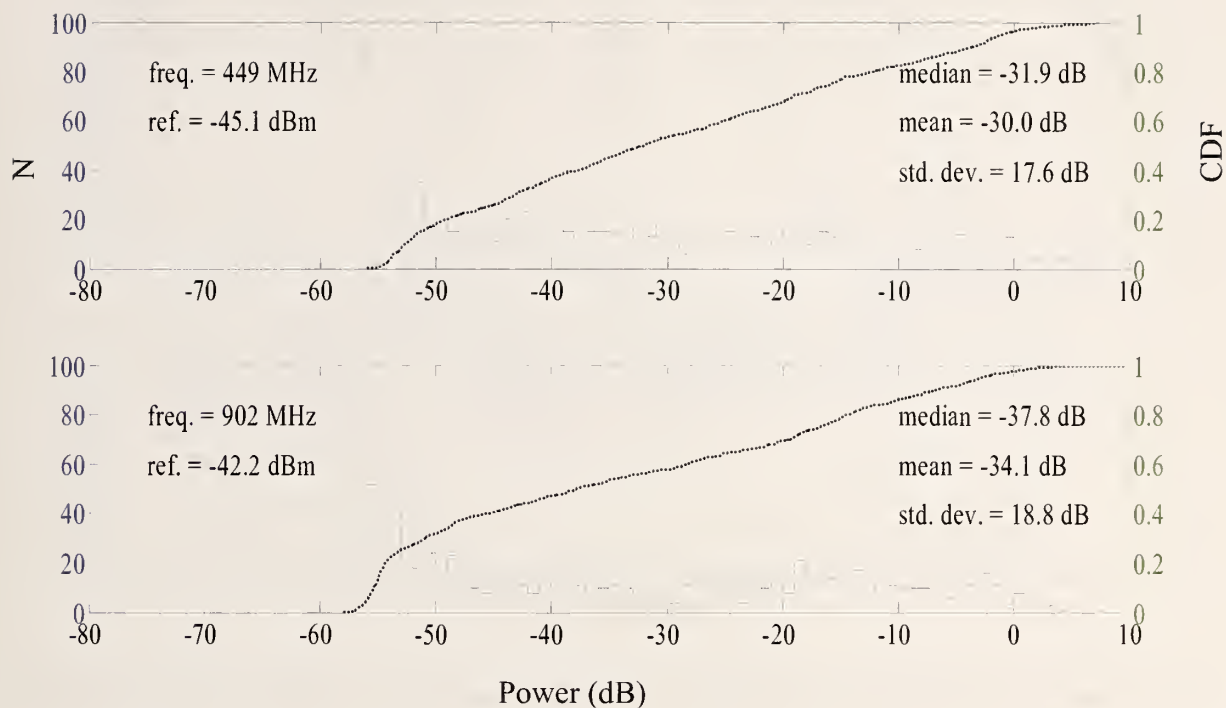


Figure 105. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for first walk-through data with the receiver at site 1; 448.50 and 902.45 MHz.



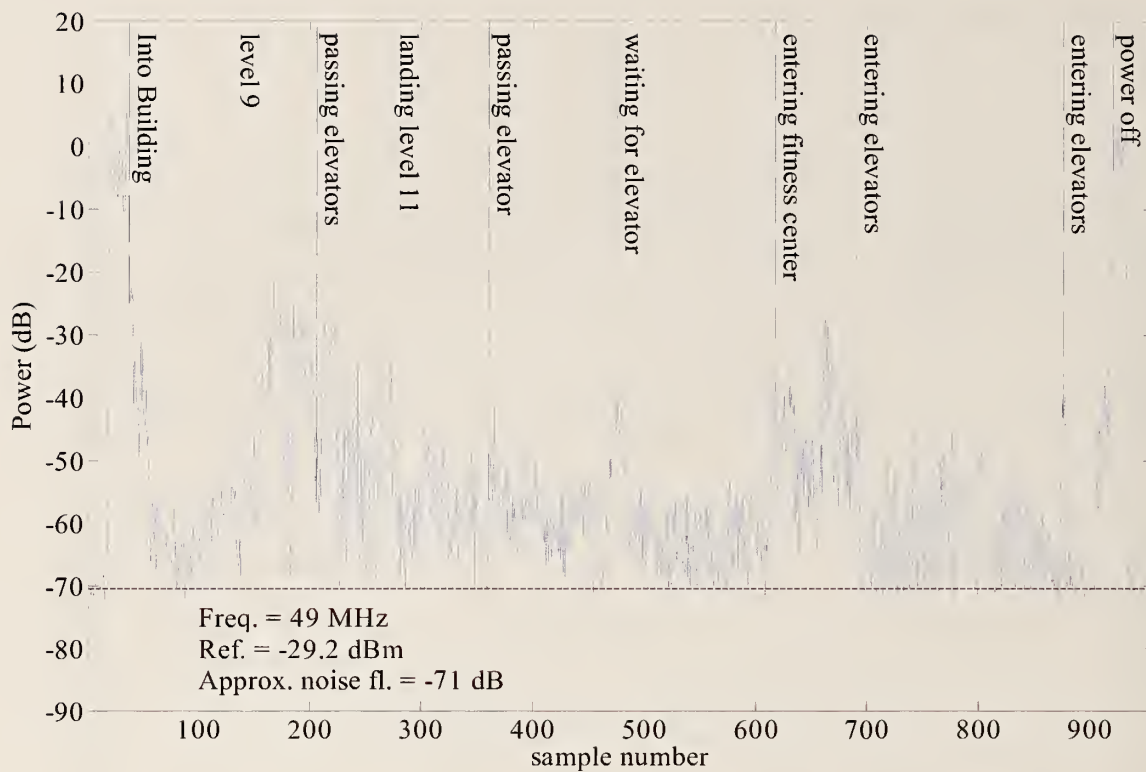


Figure 106. Colorado Springs, CO hotel second walk-through at 49.60 MHz; receiver at site 1.

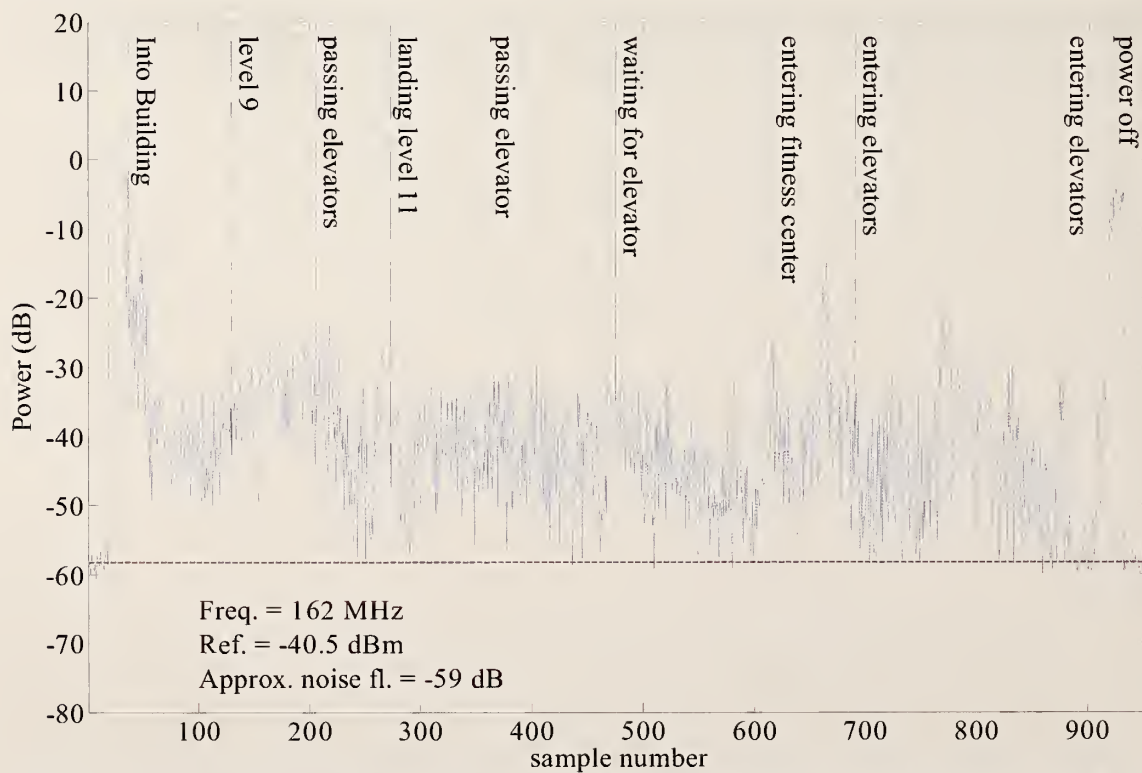


Figure 107. Colorado Springs, CO hotel second walk-through at 162.09 MHz; receiver at site 1.

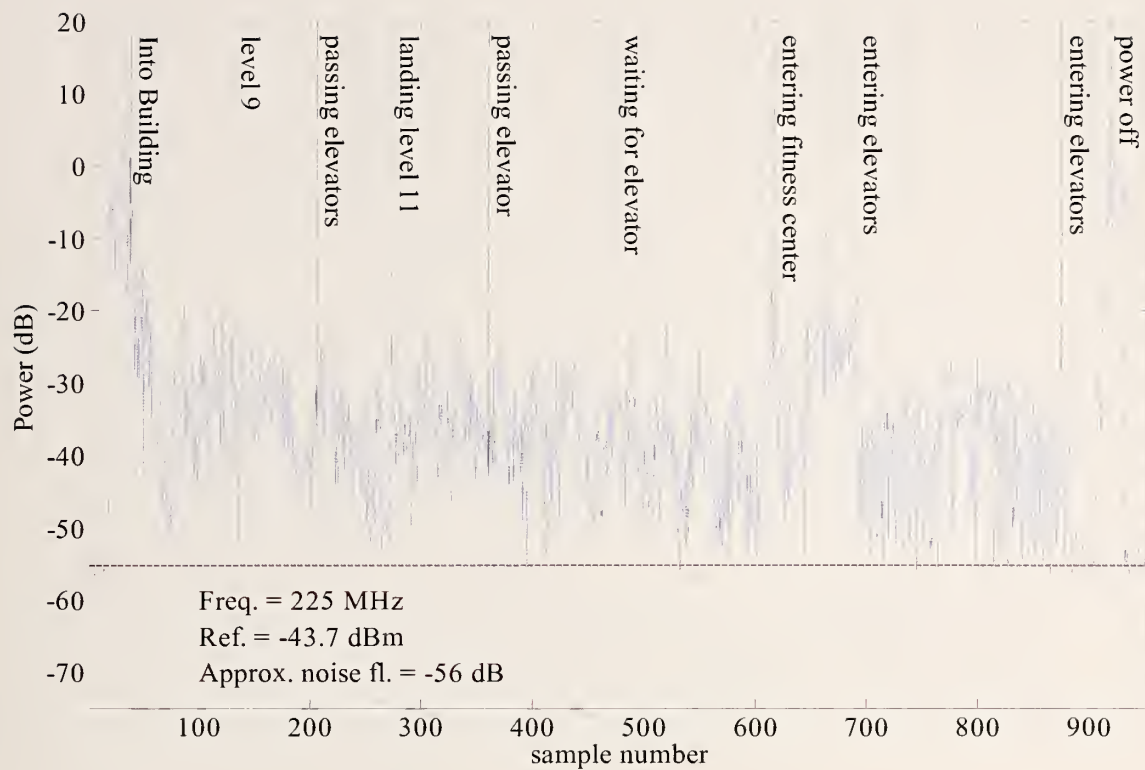


Figure 108. Colorado Springs, CO hotel second walk-through at 225.30 MHz; receiver at site 1.

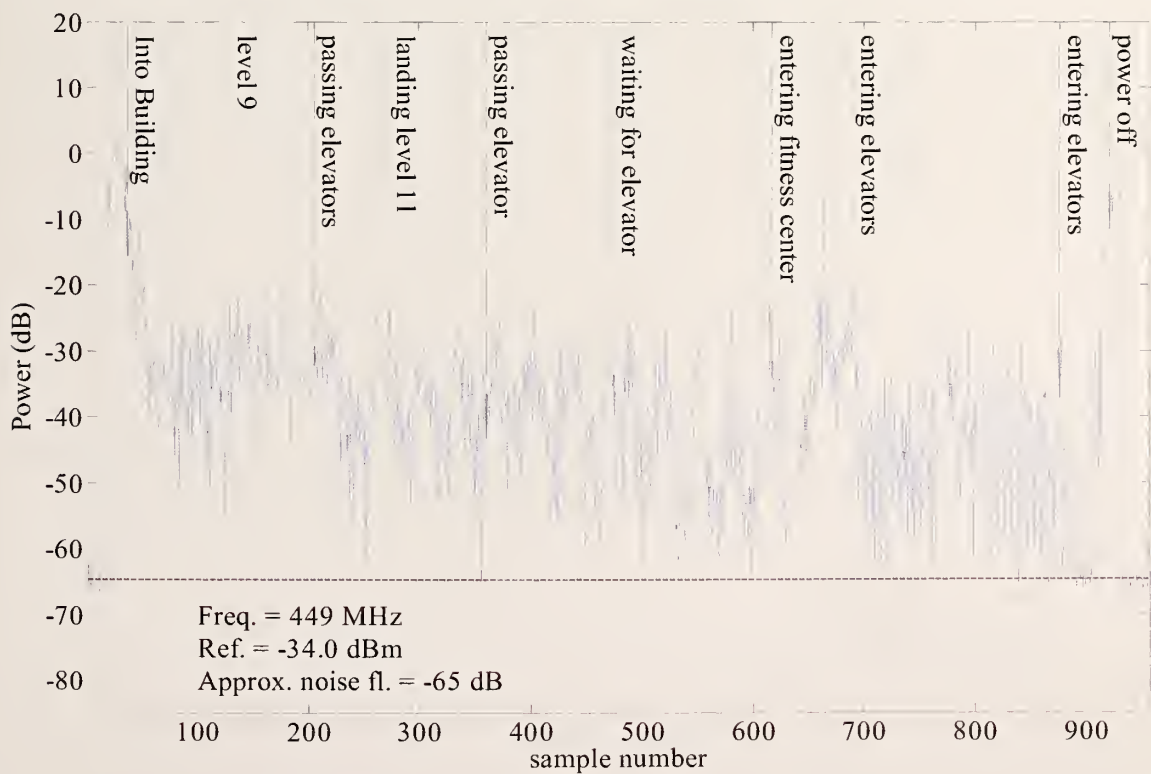


Figure 109. Colorado Springs, CO hotel second walk-through at 448.50 MHz; receiver at site 1.

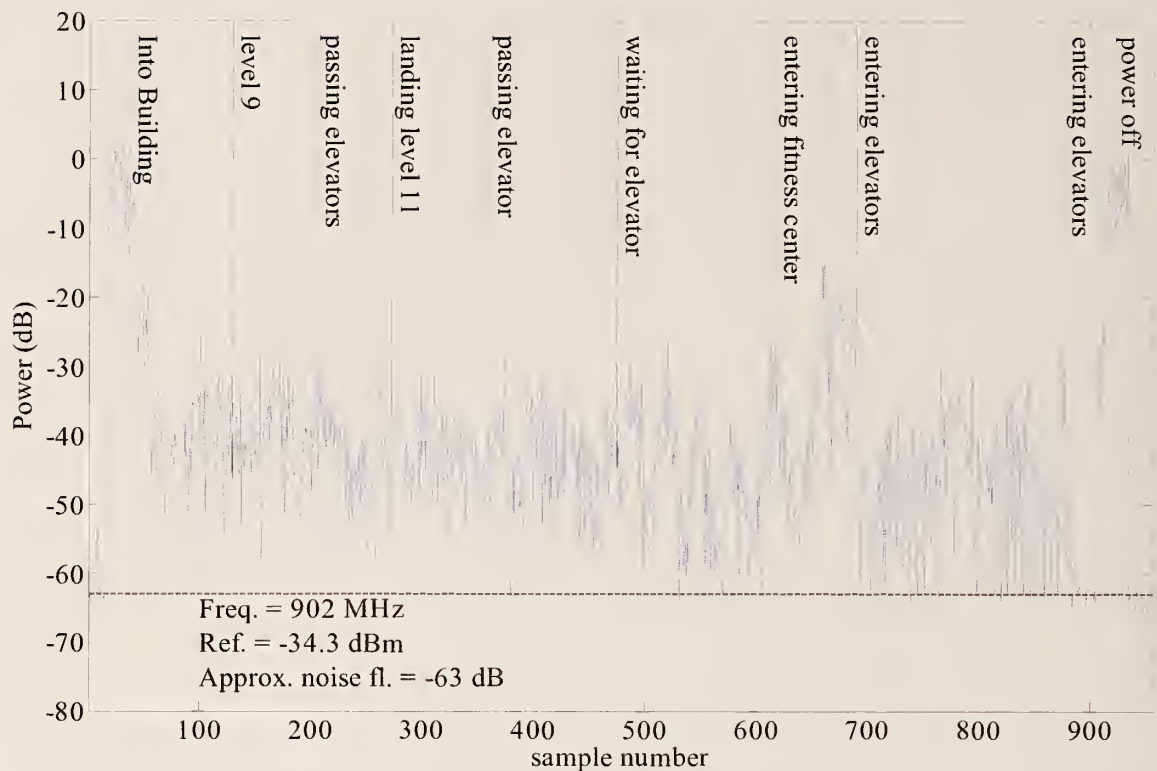


Figure 110. Colorado Springs, CO hotel second walk-through at 902.45 MHz; receiver at site 1.

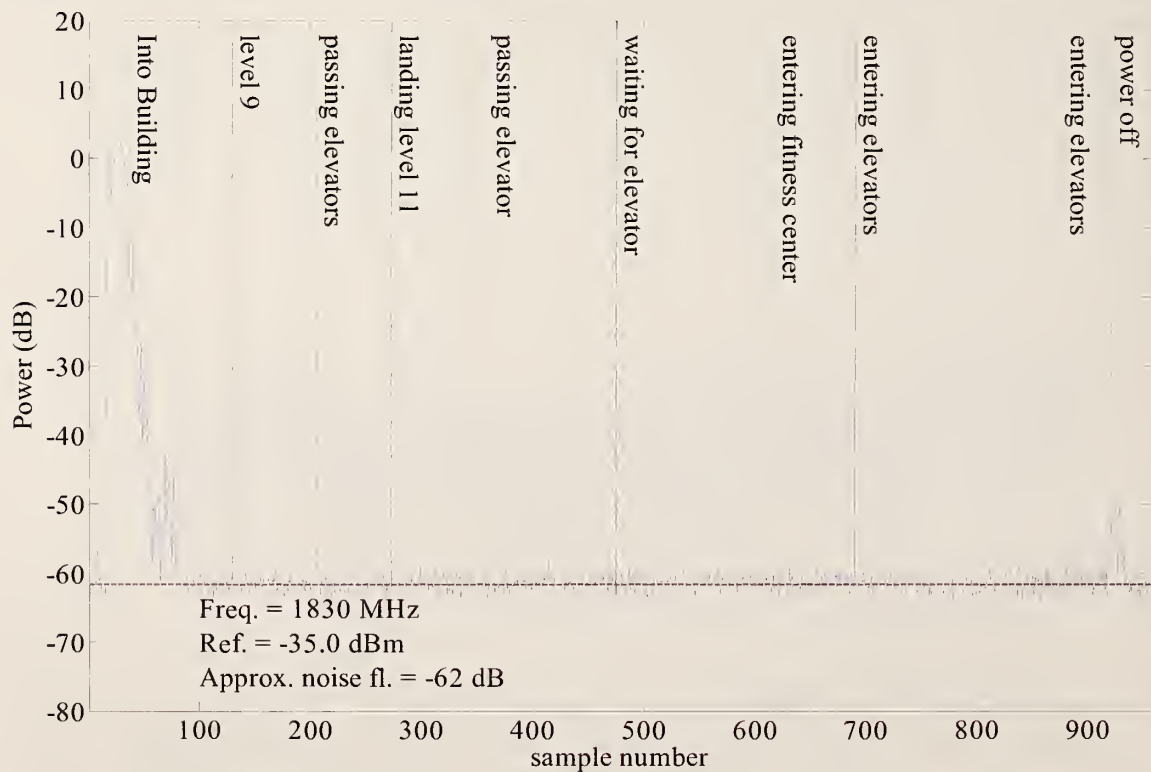


Figure 111. Colorado Springs, CO hotel second walk-through at 1830.00 MHz; receiver at site 1.



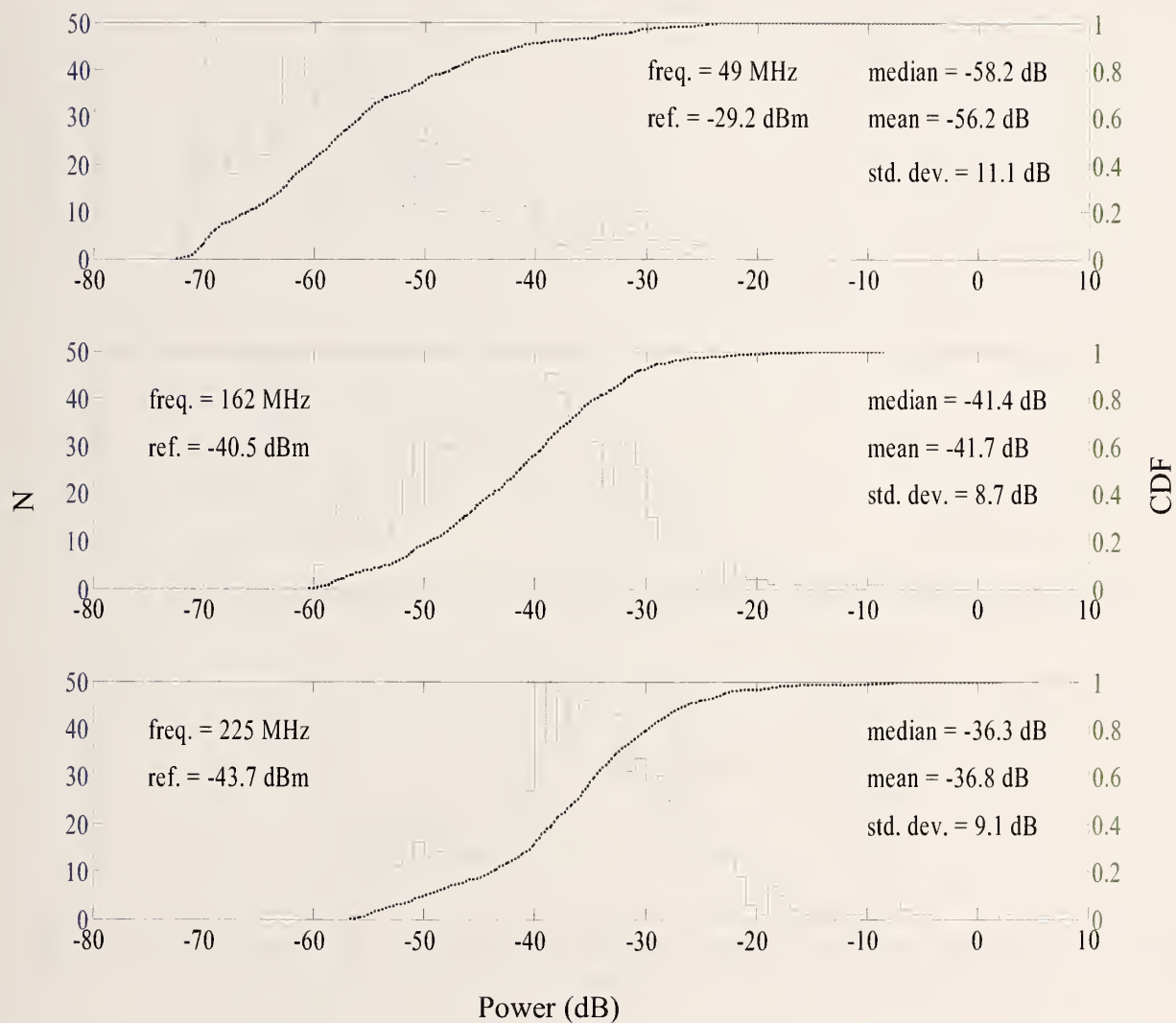


Figure 112. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for second walk-through data with the receiver at site 1; 49.60, 162.09, and 225.30 MHz.

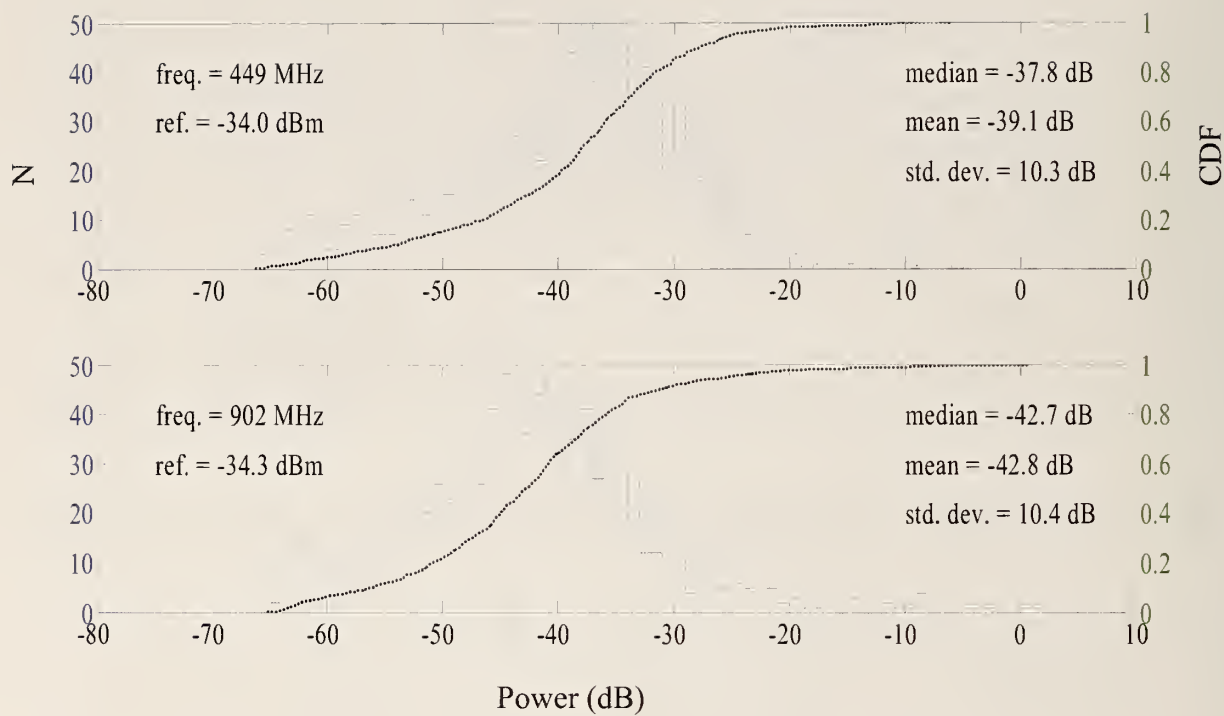


Figure 113. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for second walk-through data with the receiver at site 1; 448.50 and 902.45 MHz.

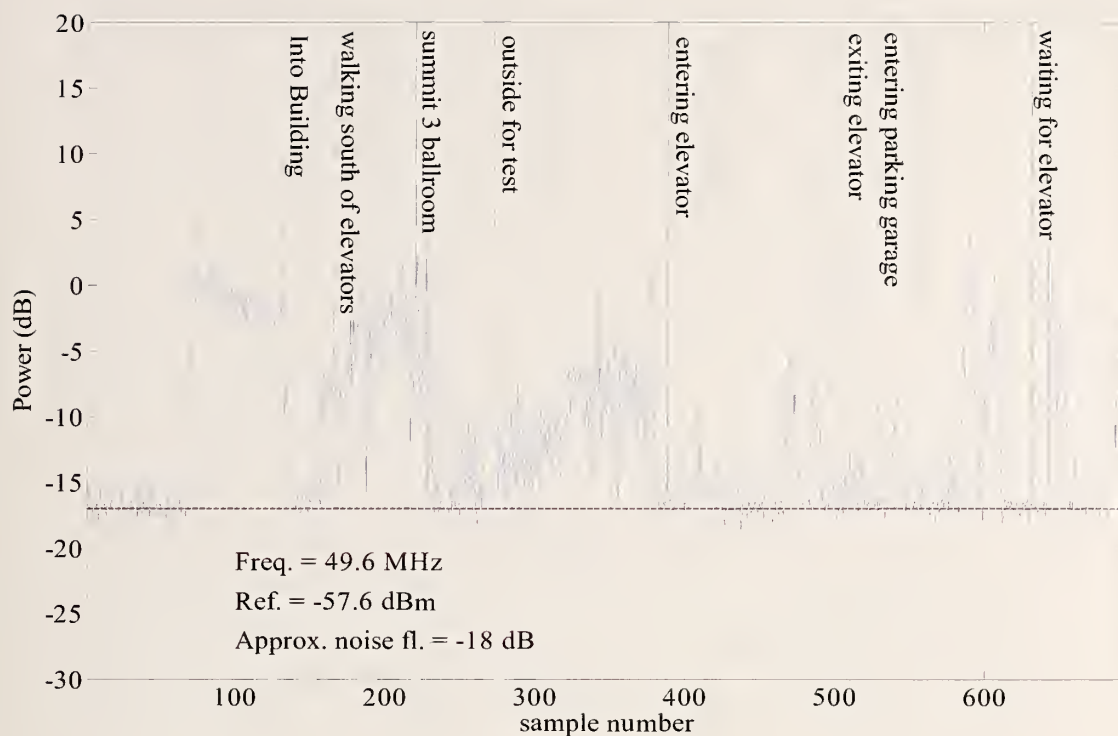


Figure 114. Colorado Springs, CO hotel first walk-through at 49.60 MHz; receiver at site 2.

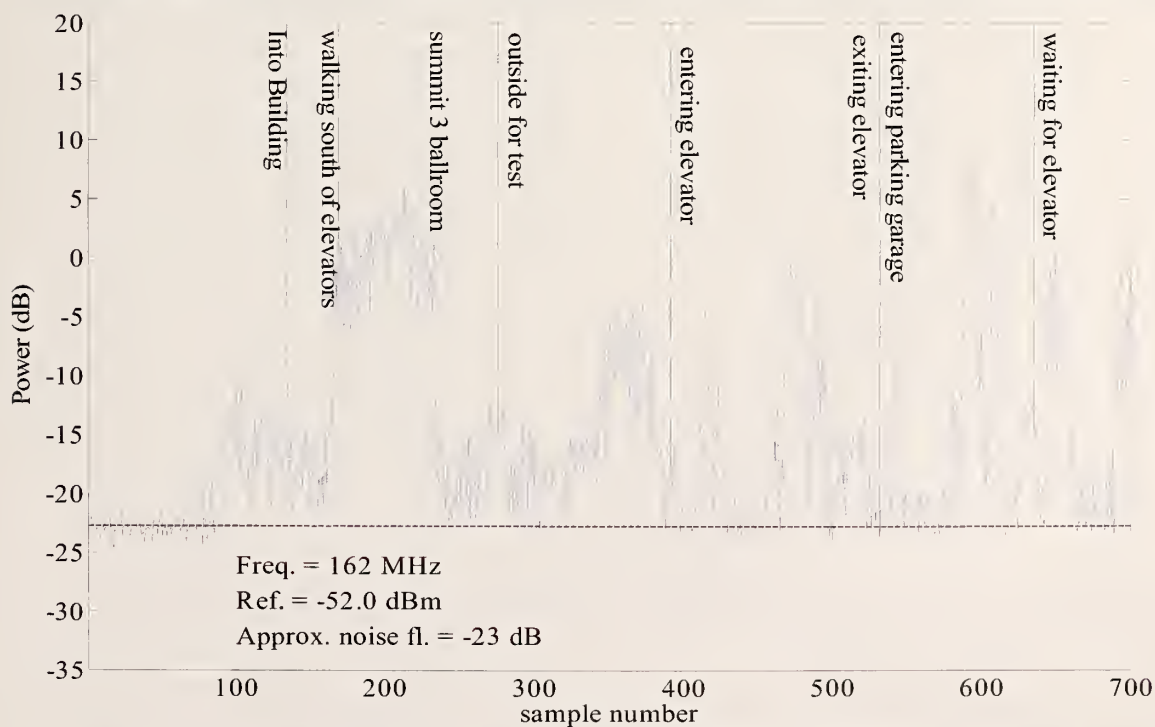


Figure 115. Colorado Springs, CO hotel first walk-through at 162.09 MHz; receiver at site 2.



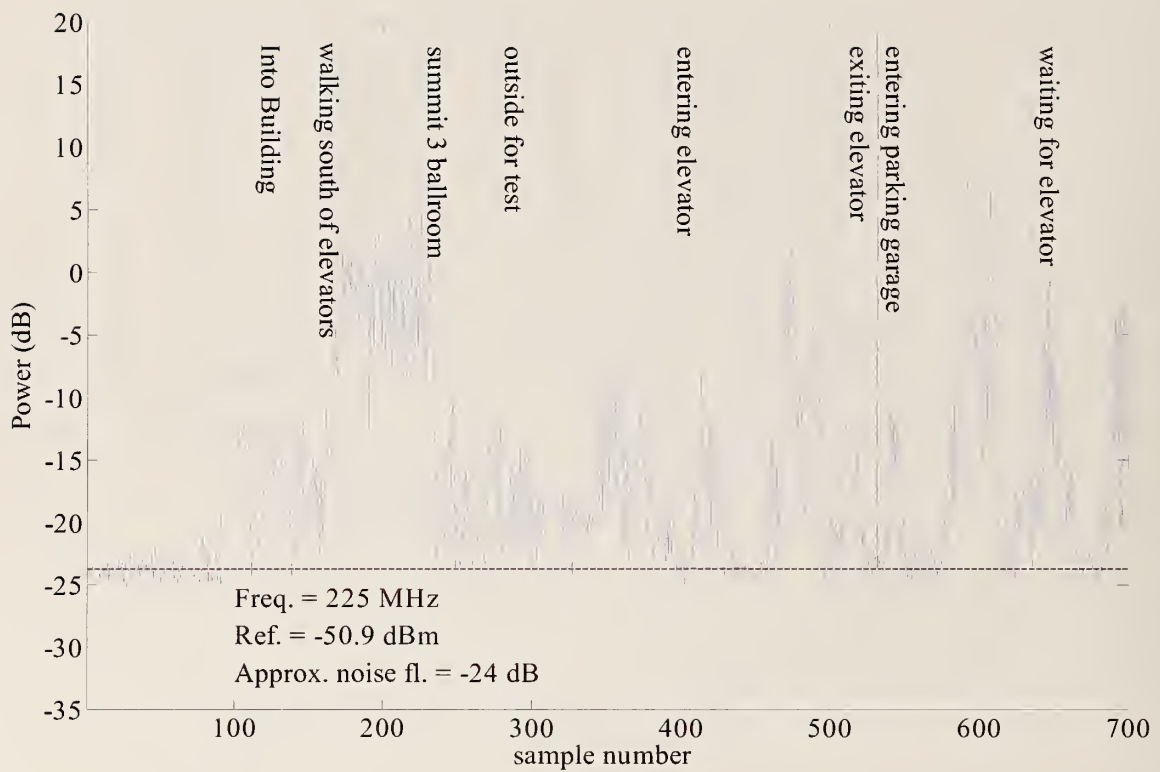


Figure 116. Colorado Springs, CO hotel first walk-through at 225.30 MHz; receiver at site 2.

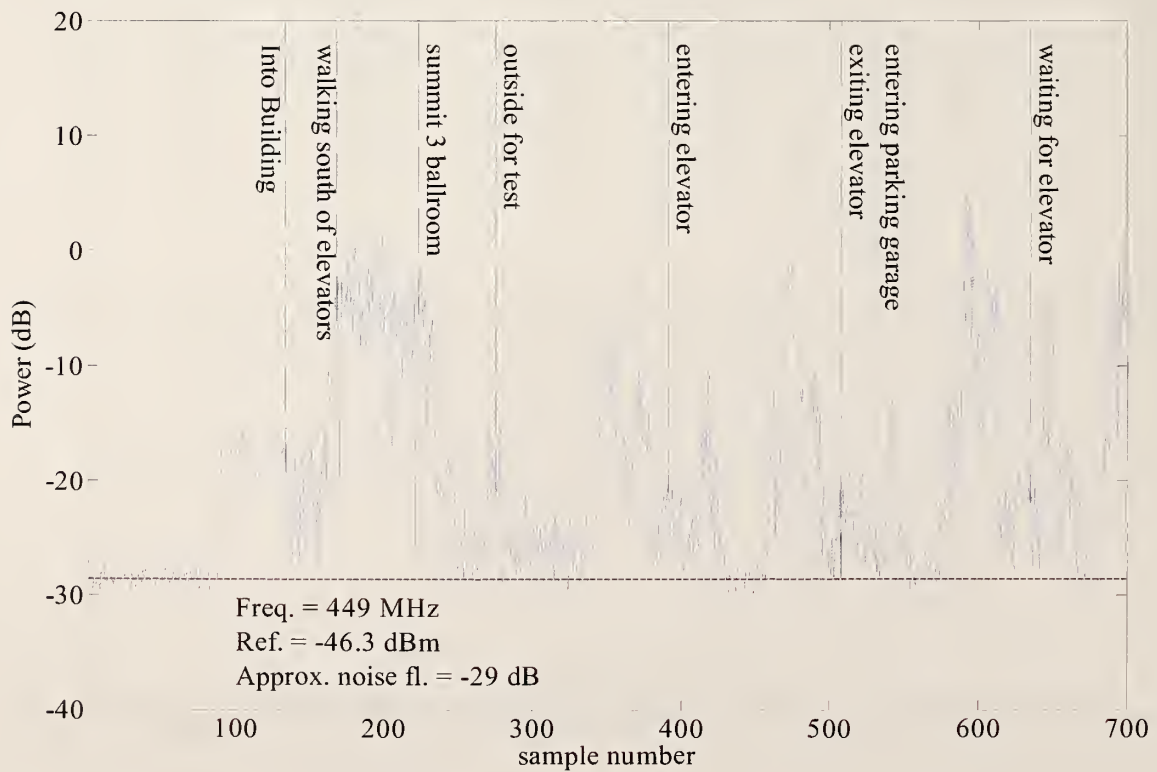


Figure 117. Colorado Springs, CO hotel first walk-through at 448.50 MHz; receiver at site 2.

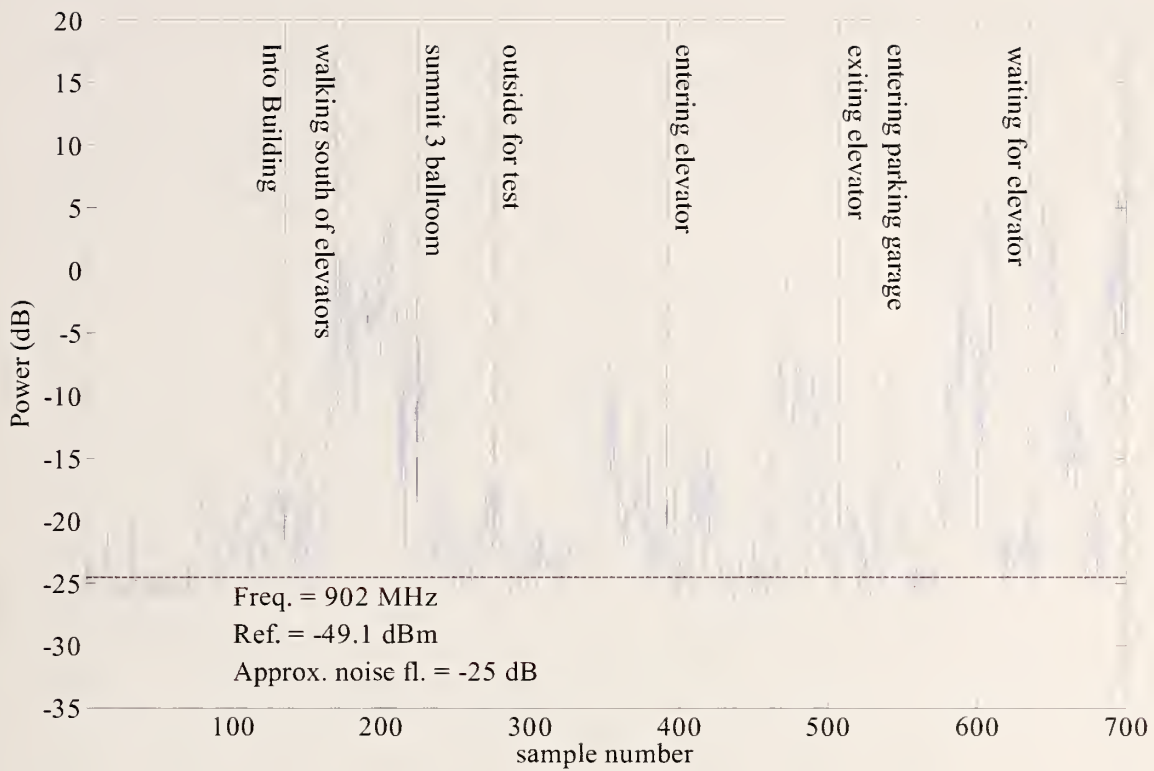


Figure 118. Colorado Springs, CO hotel first walk-through at 902.45 MHz; receiver at site 2.

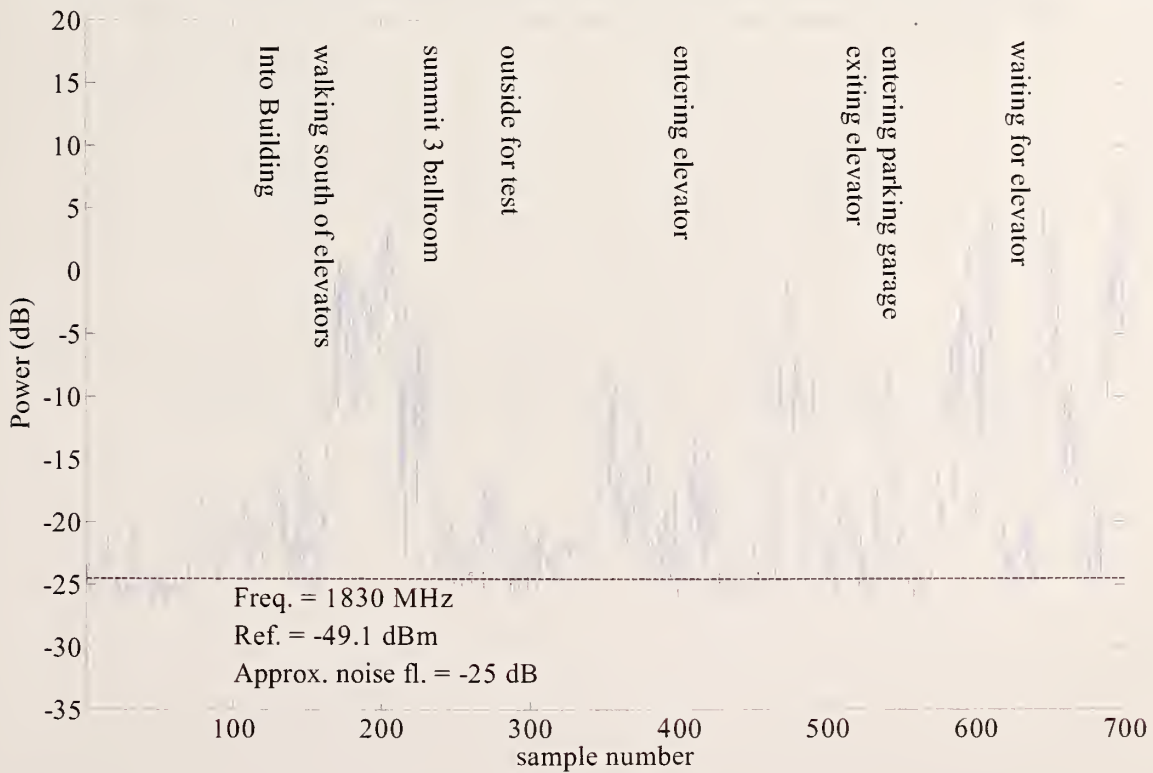


Figure 119. Colorado Springs, CO hotel first walk-through at 1830.00 MHz; receiver at site 2.

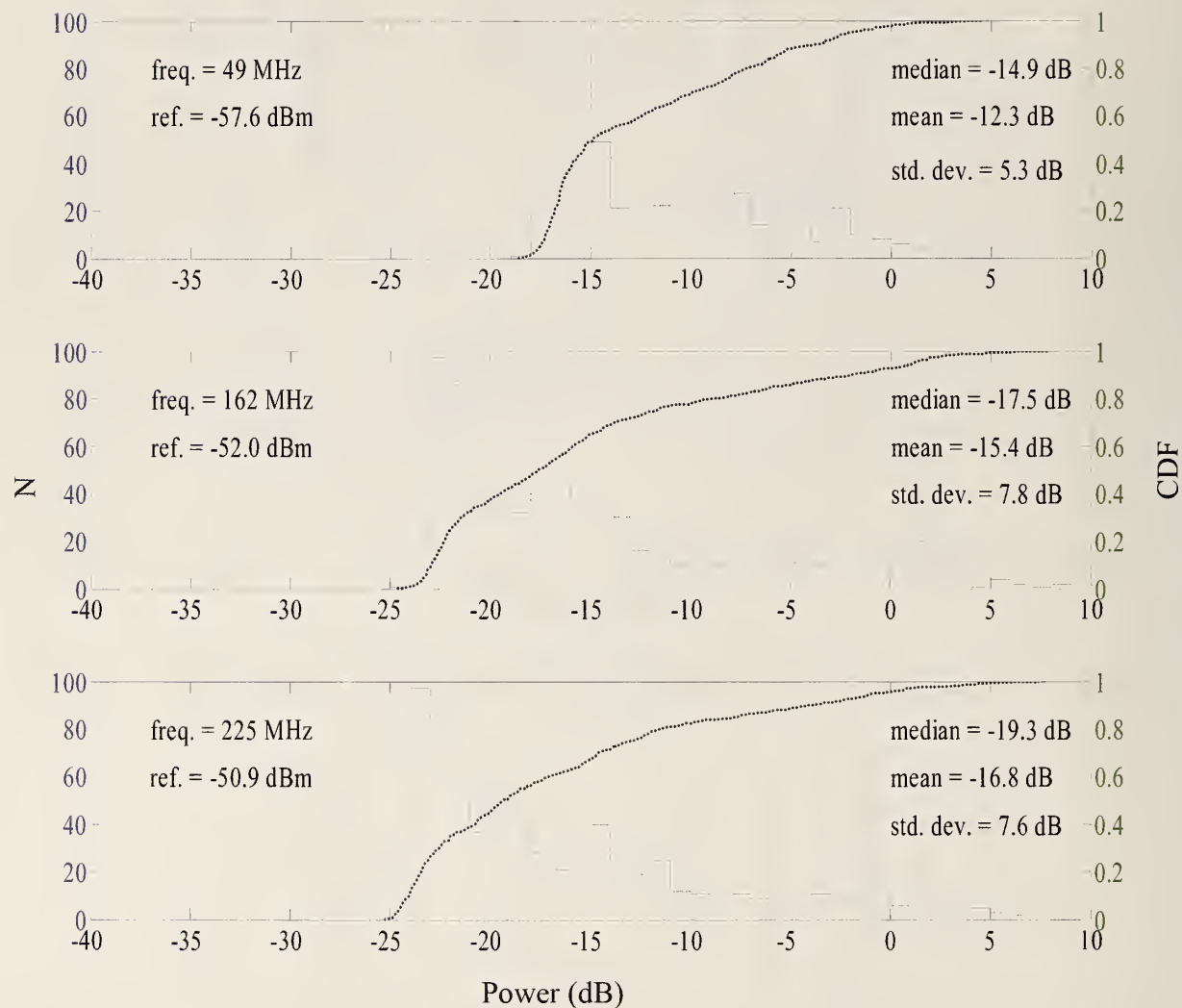


Figure 120. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for first walk-through data with the receiver at site 2; 49.60, 162.09, and 225.30 MHz.



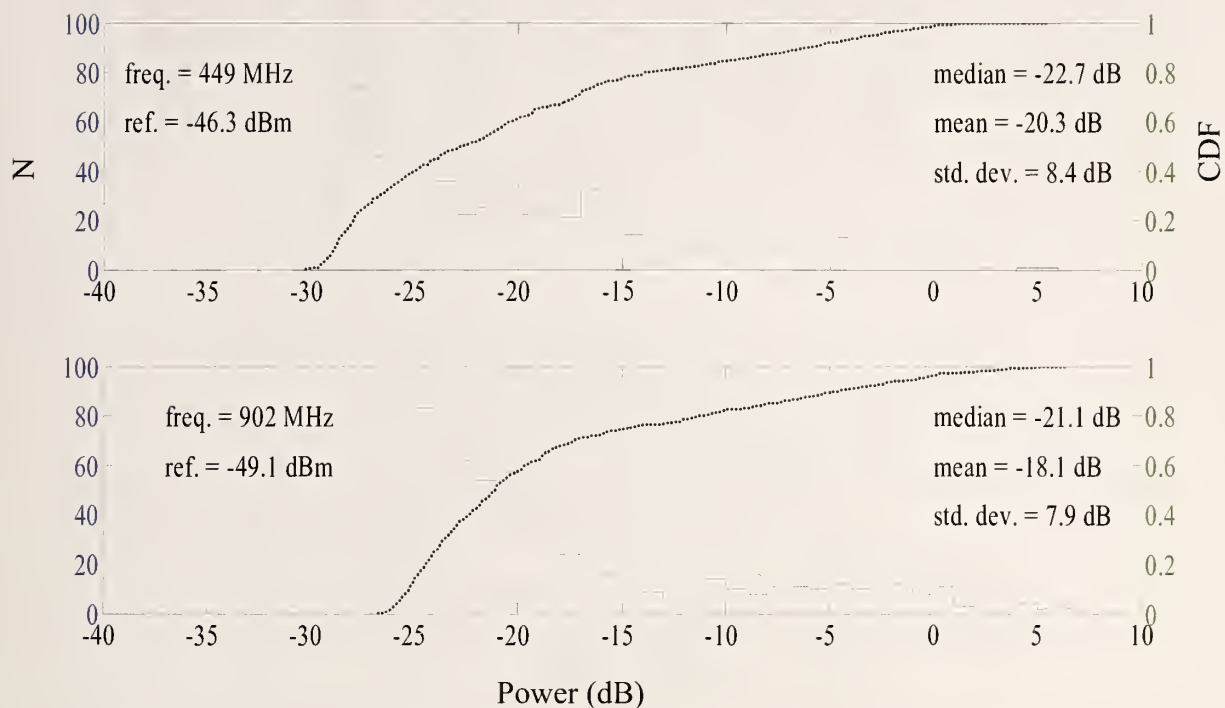


Figure 121. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for first walk-through data with the receiver at site 2; 448.50 and 902.45 MHz.

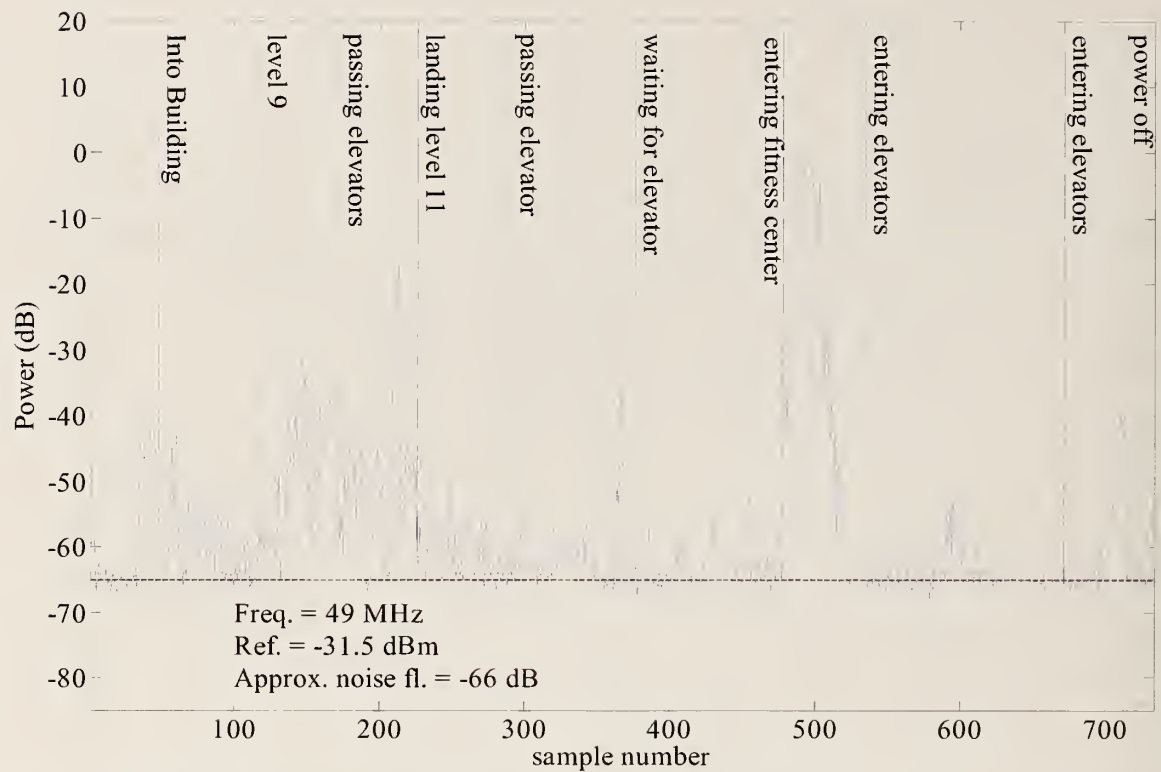


Figure 122. Colorado Springs, CO hotel second walk-through at 49.60 MHz; receiver at site 2.

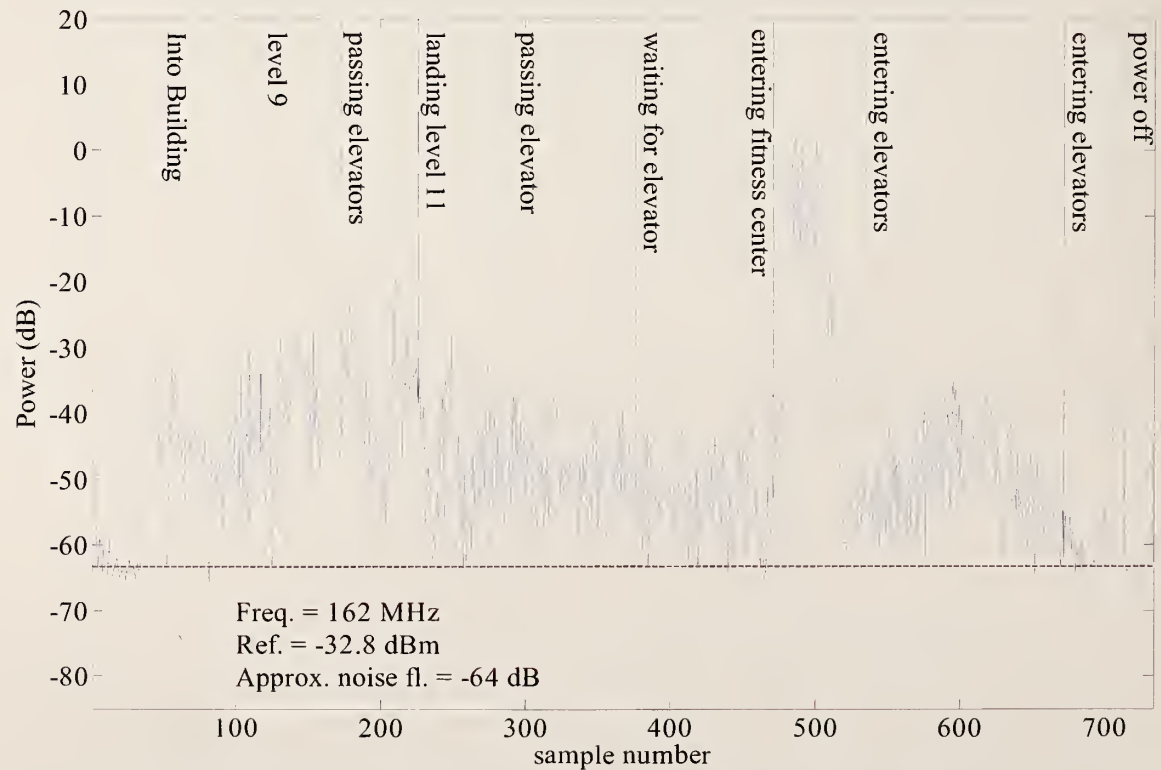


Figure 123. Colorado Springs, CO hotel second walk-through at 162.09 MHz; receiver at site 2.

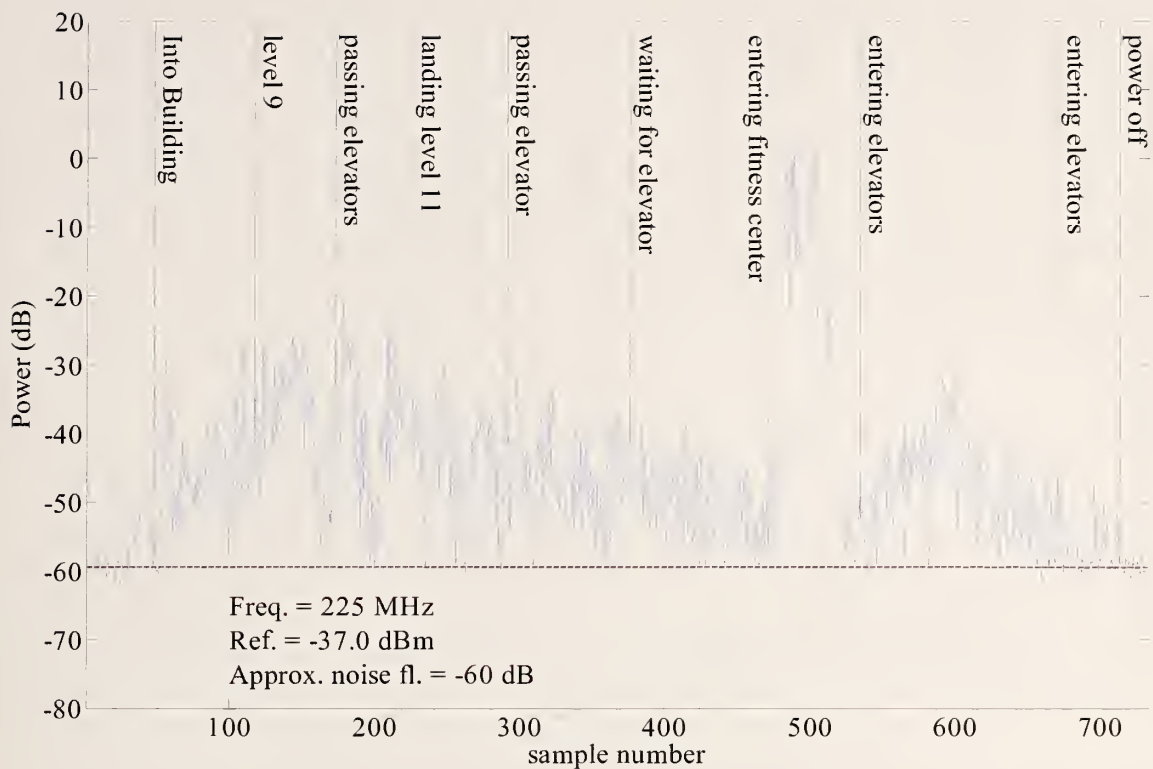


Figure 124. Colorado Springs, CO hotel second walk-through at 225.30 MHz; receiver at site 2.

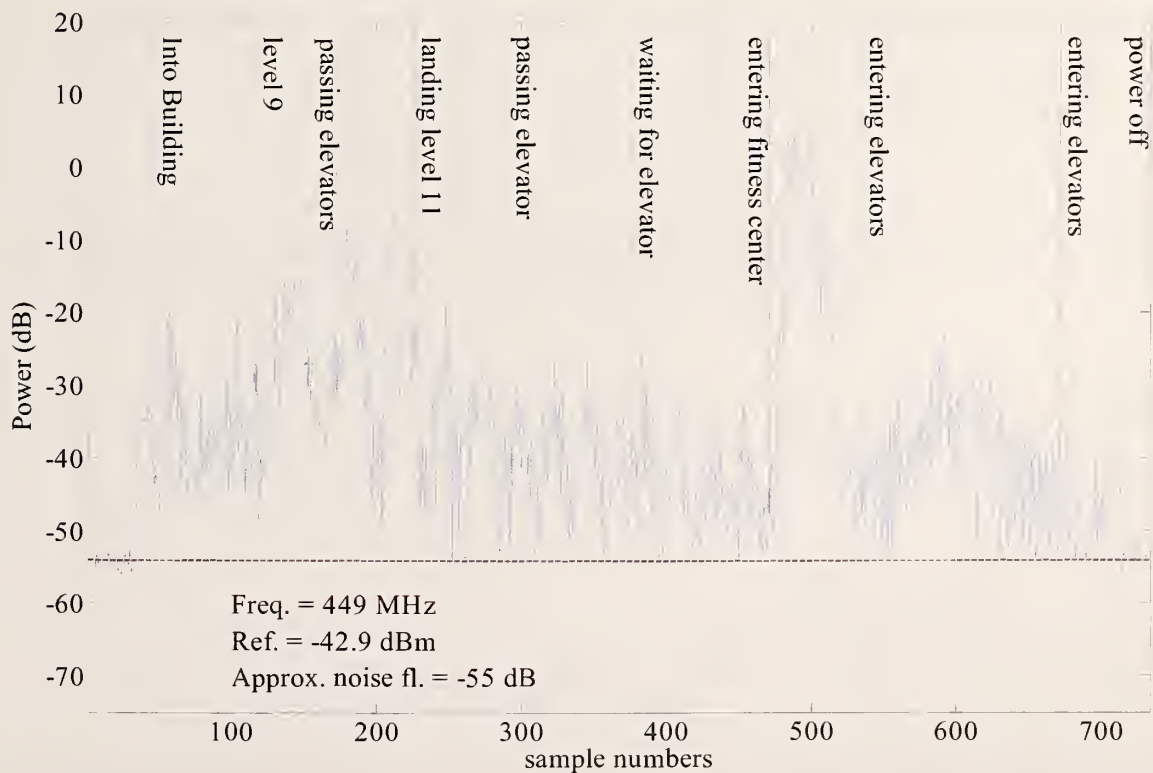


Figure 125. Colorado Springs, CO hotel second walk-through at 448.50 MHz; receiver at site 2.



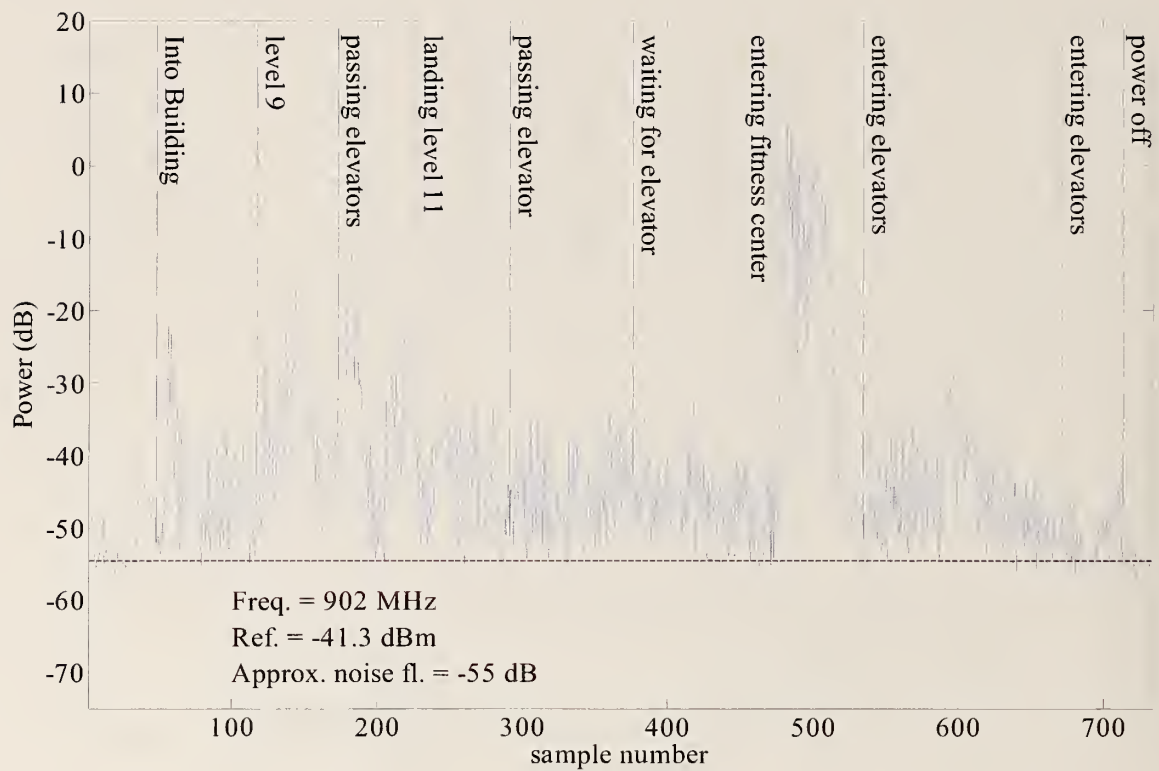


Figure 126. Colorado Springs, CO hotel second walk-through at 902.45 MHz; receiver at site 2.

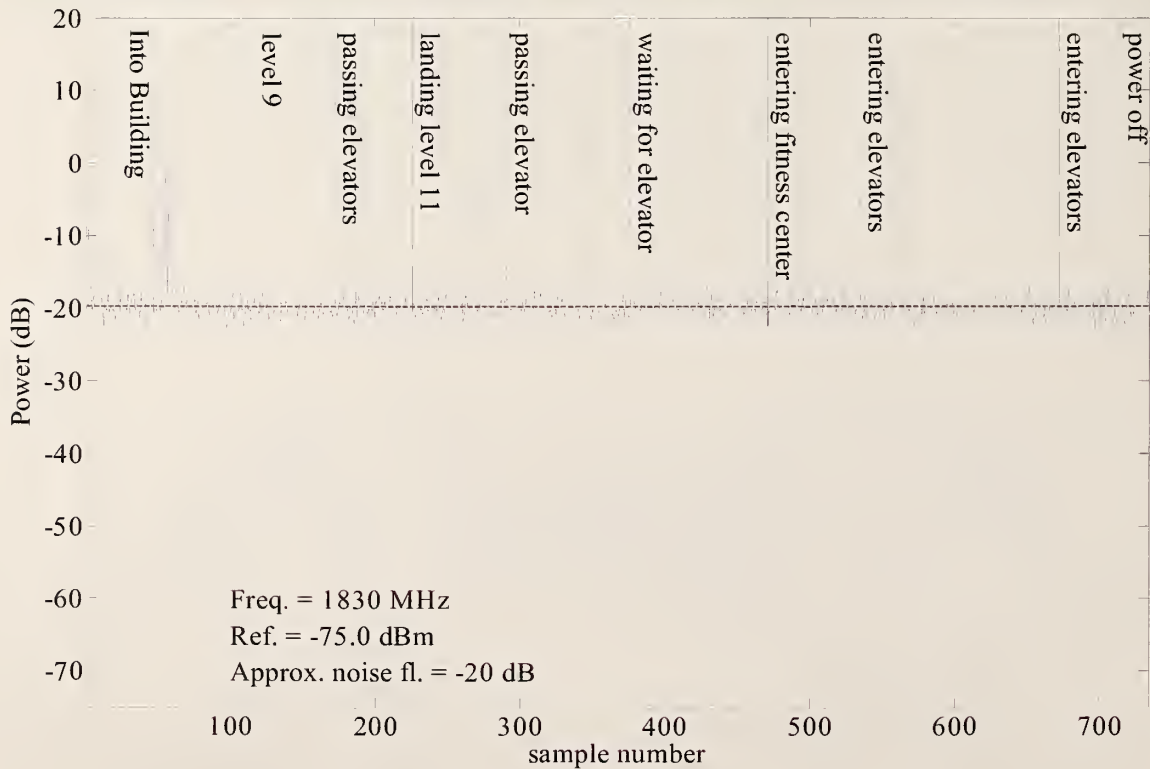


Figure 127. Colorado Springs, CO hotel second walk-through at 1830.00 MHz; receiver at site 2.

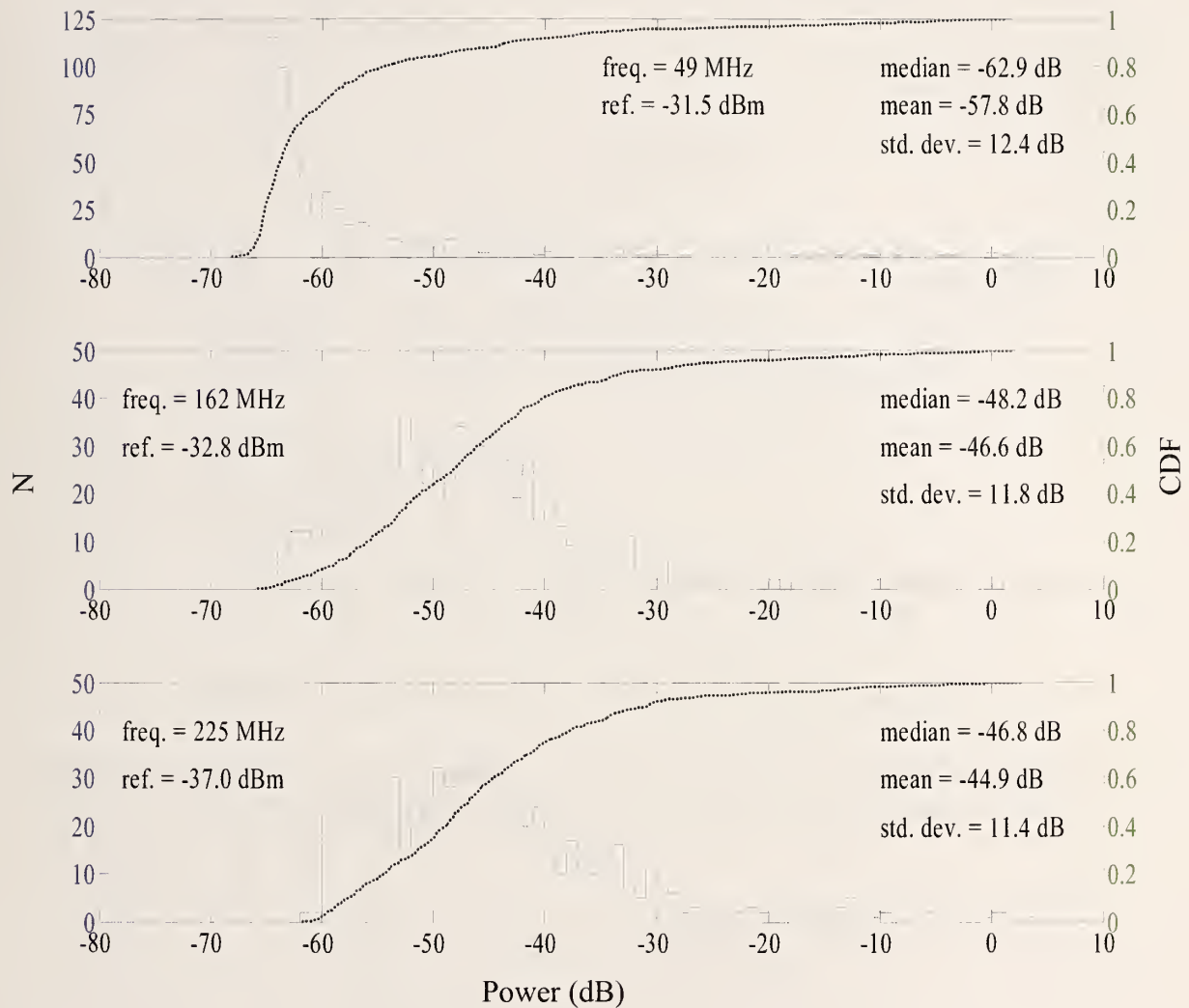


Figure 128. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for second walk-through data with the receiver at site 2; 49.60, 162.09, and 225.30 MHz.

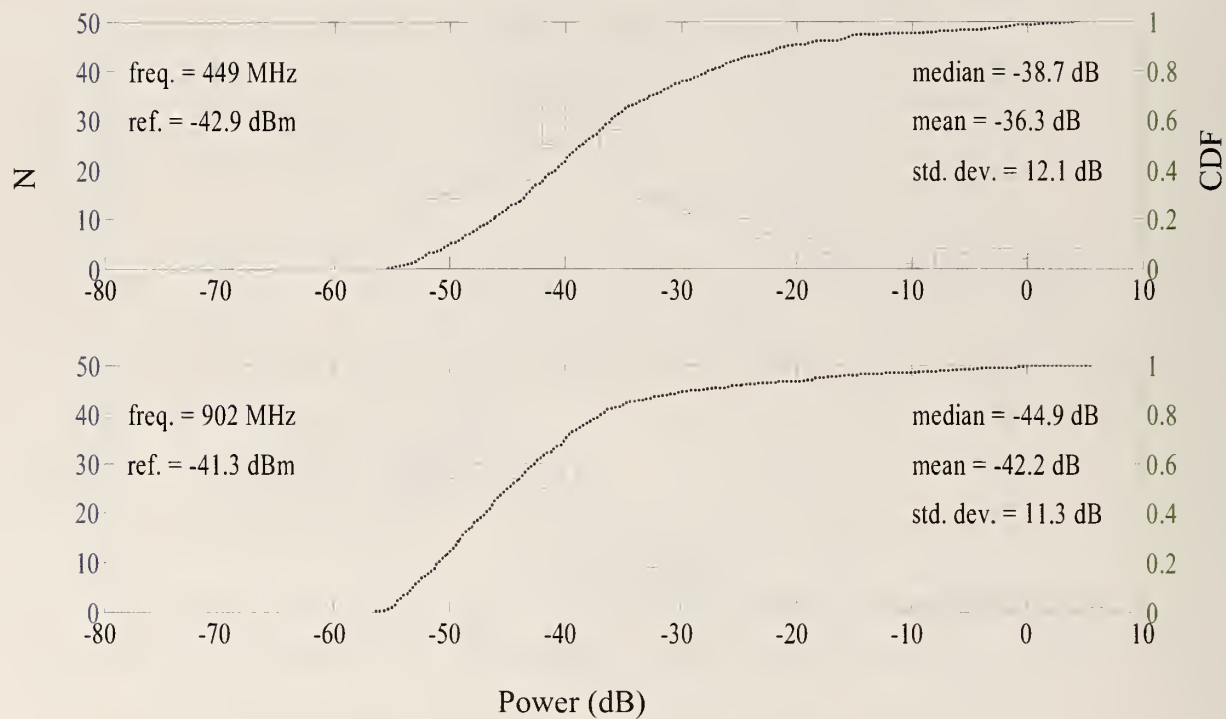


Figure 129. Colorado Springs, CO hotel statistics, histograms, and empirical CDF for second walk-through data with the receiver at site 2; 448.50 and 902.45 MHz.



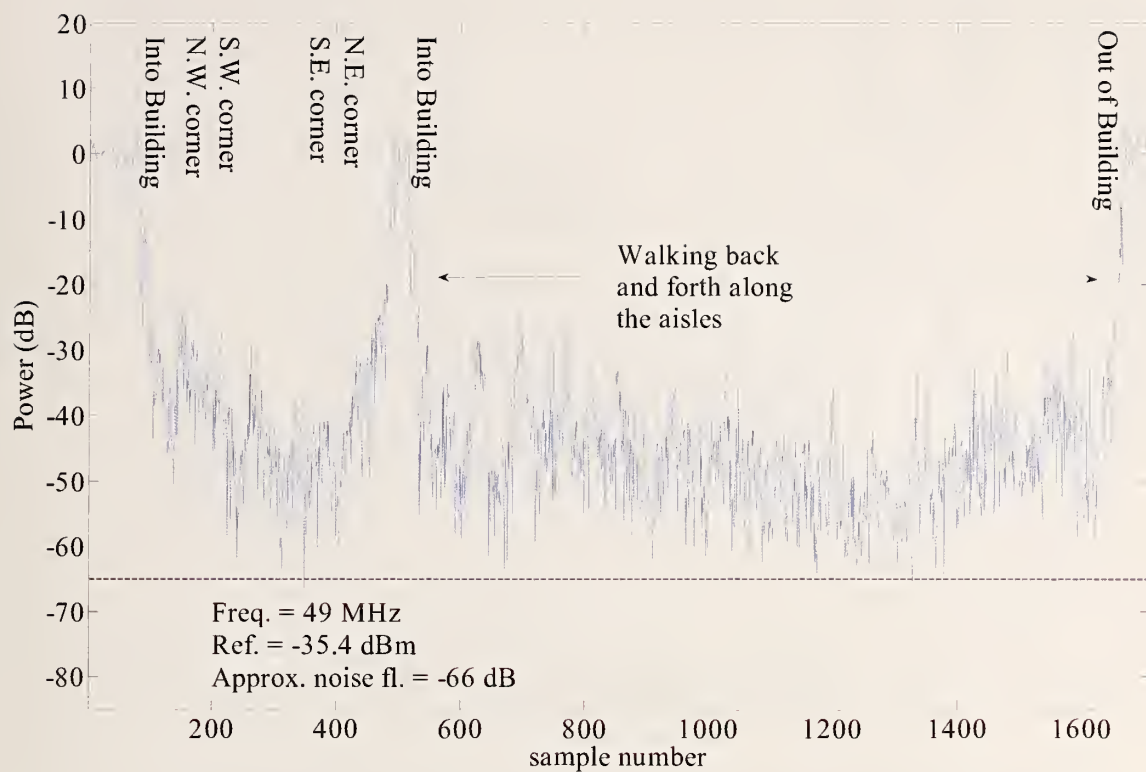


Figure 130. Boulder, CO grocery store walk-through at 49.60 MHz.

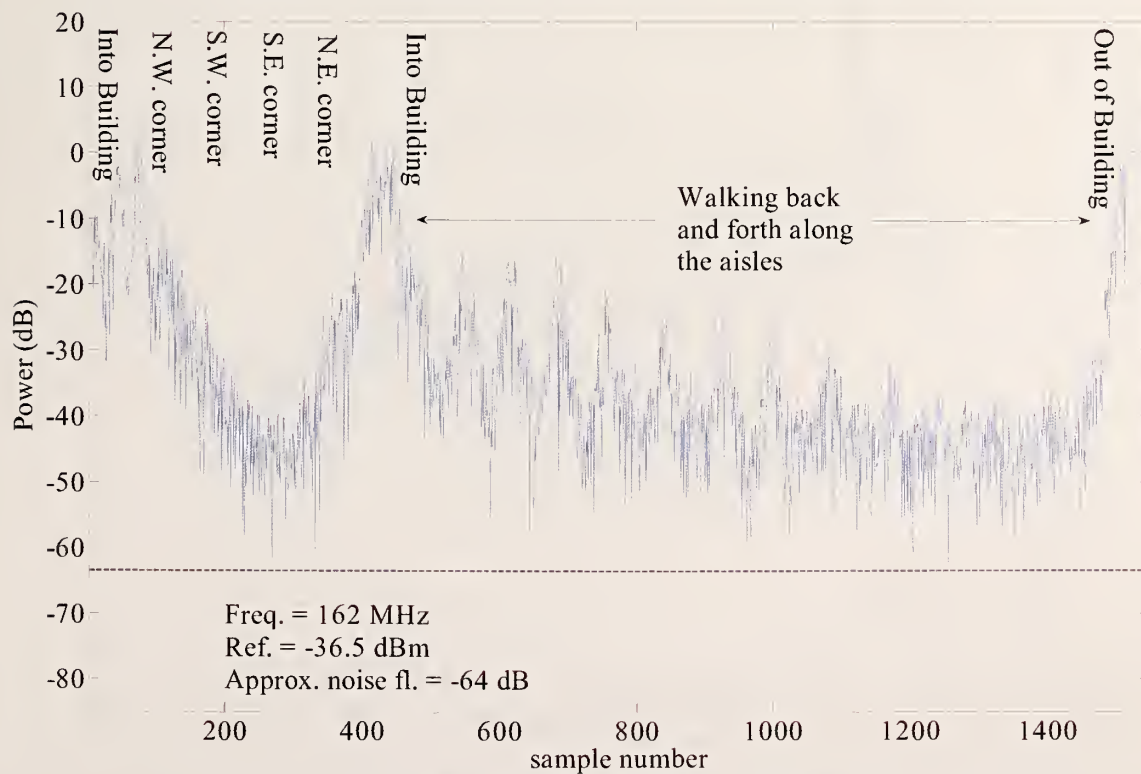


Figure 131. Boulder, CO grocery store walk-through at 162.09 MHz.

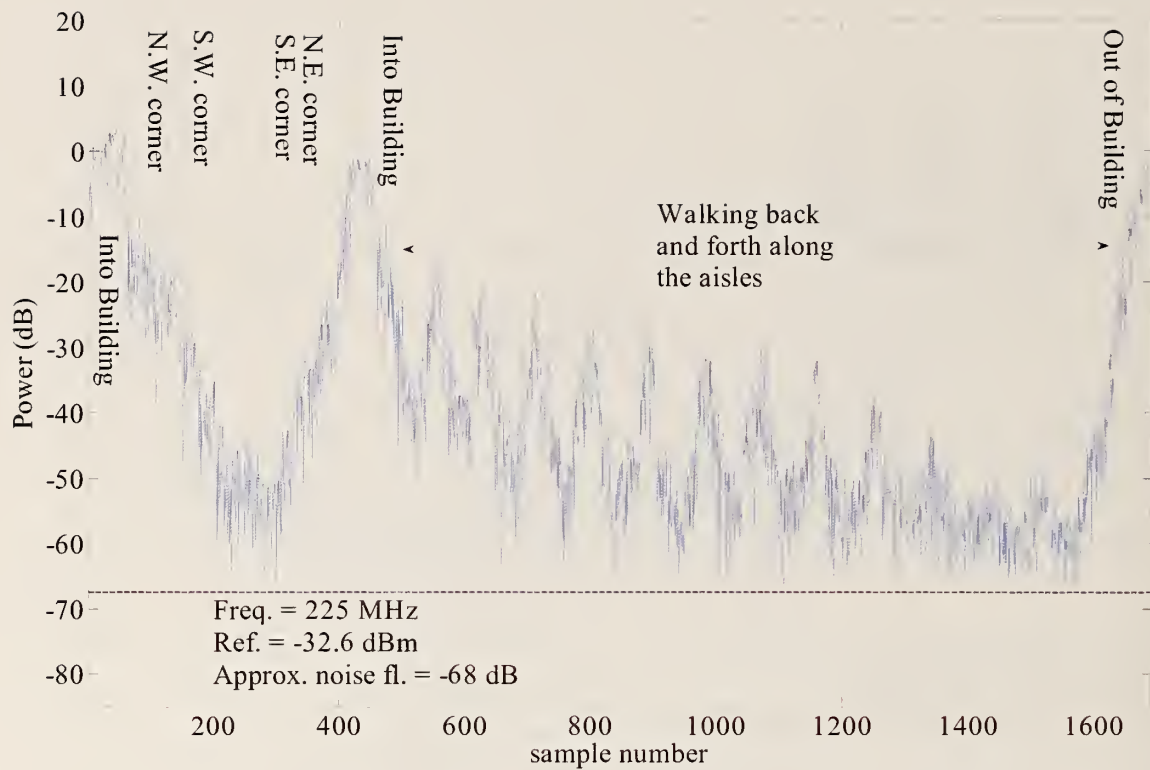


Figure 132. Boulder, CO grocery store walk-through at 225.30 MHz.

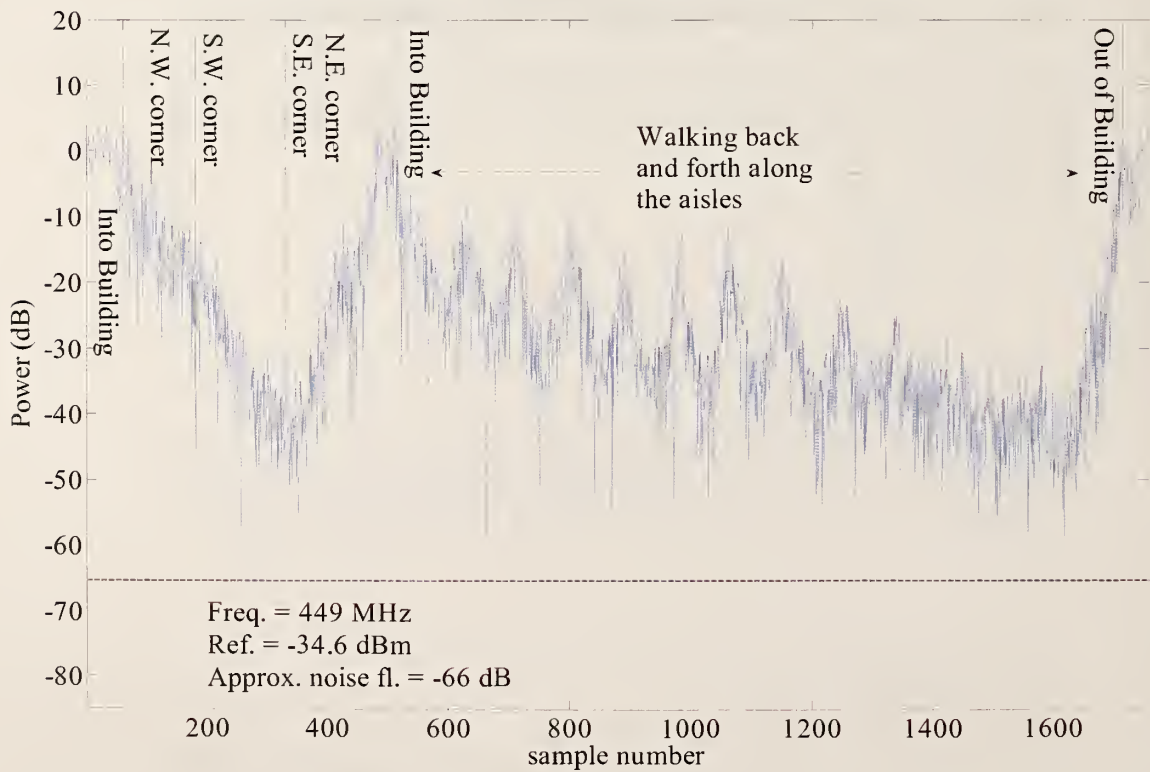


Figure 133. Boulder, CO grocery store walk-through at 448.50 MHz.

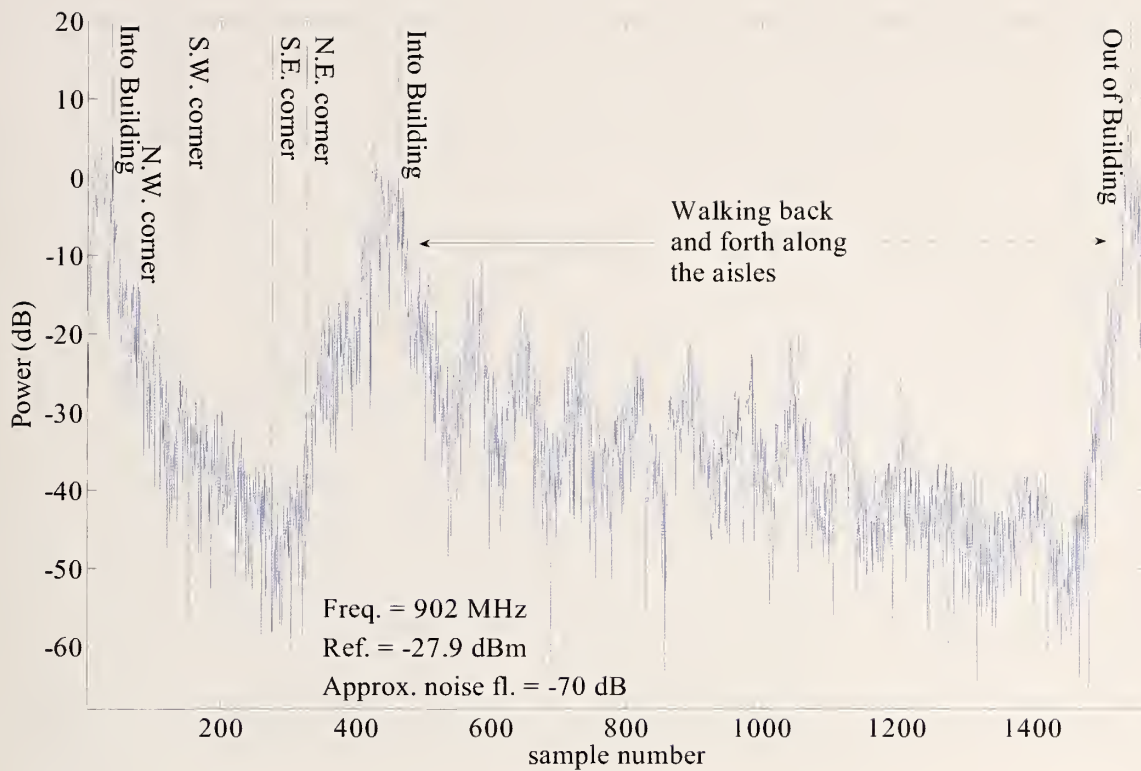


Figure 134. Boulder, CO grocery store walk-through at 902.75 MHz.

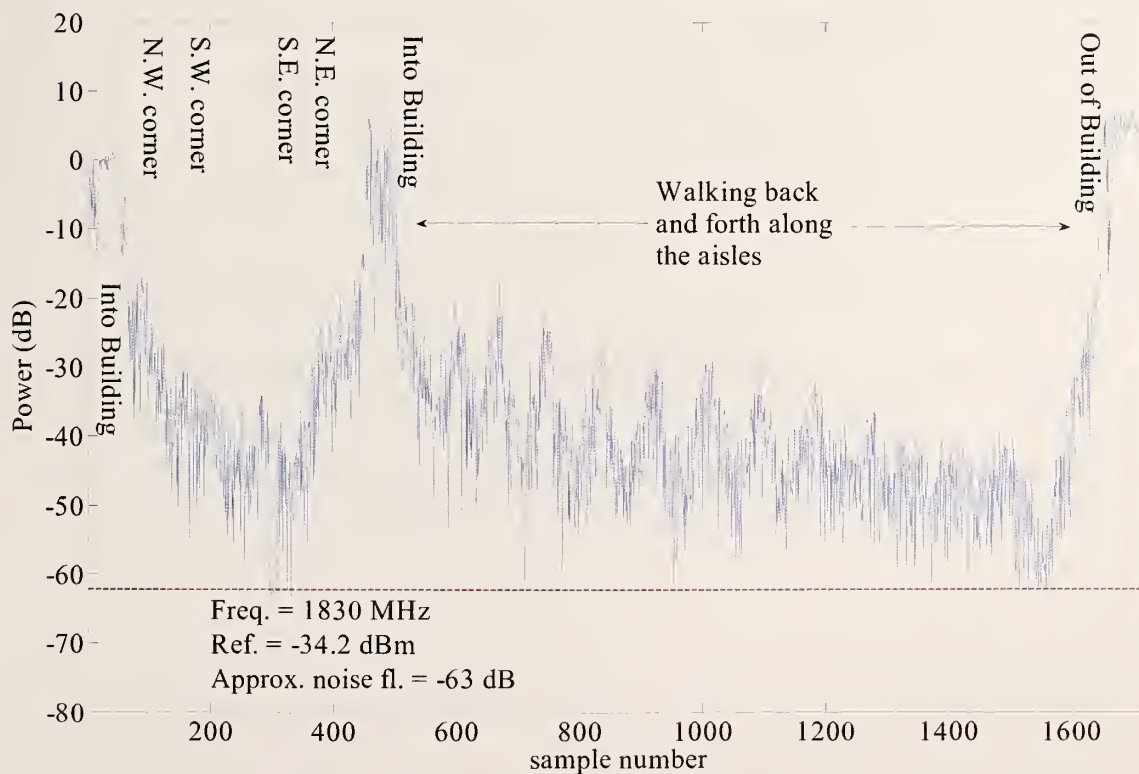


Figure 135. Boulder, CO grocery store walk-through at 1830.00 MHz.



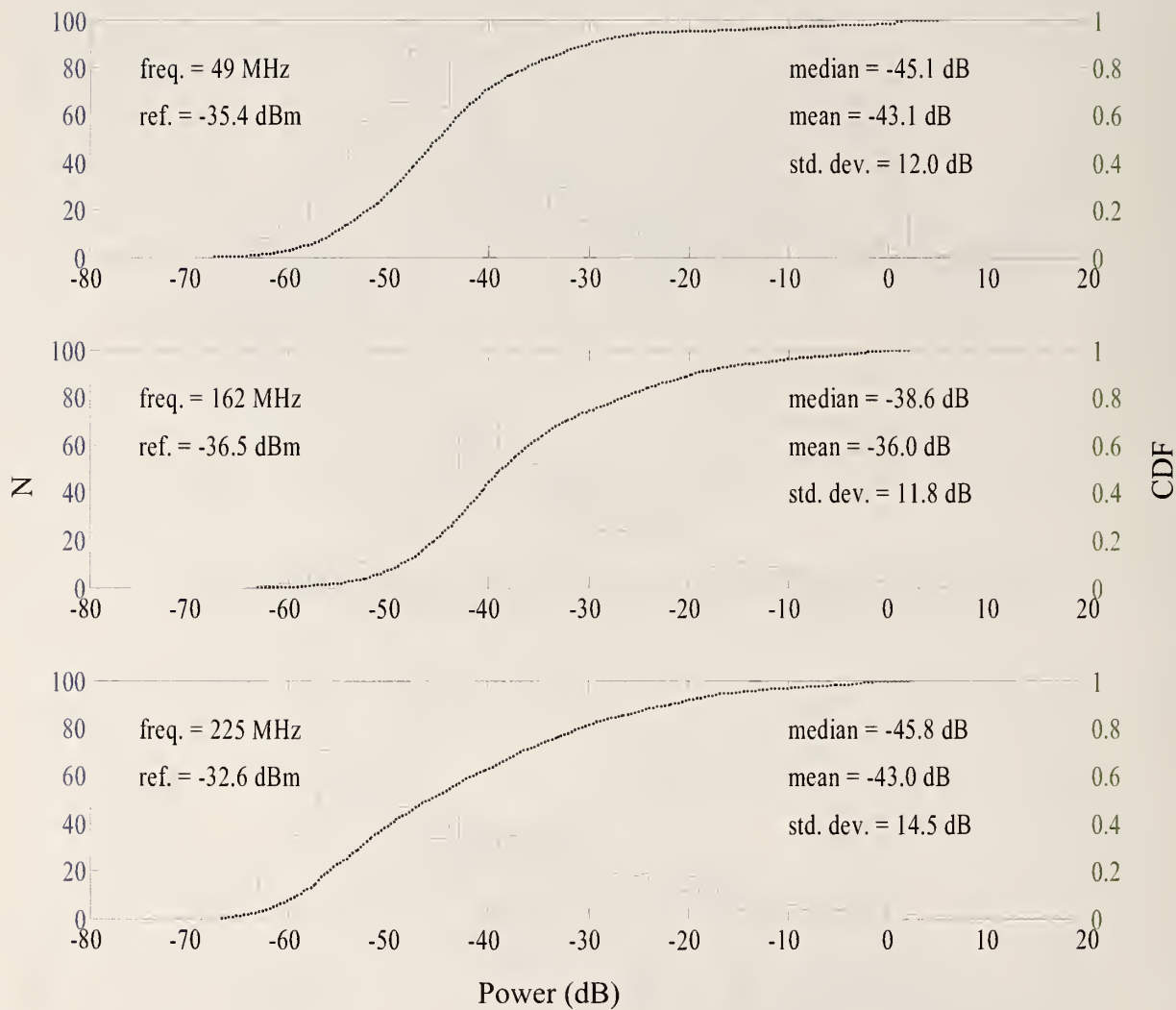


Figure 136. Boulder, CO grocery store statistics, histograms, and empirical CDF for walk-through data; 49.60, 162.09, and 225.30 MHz.

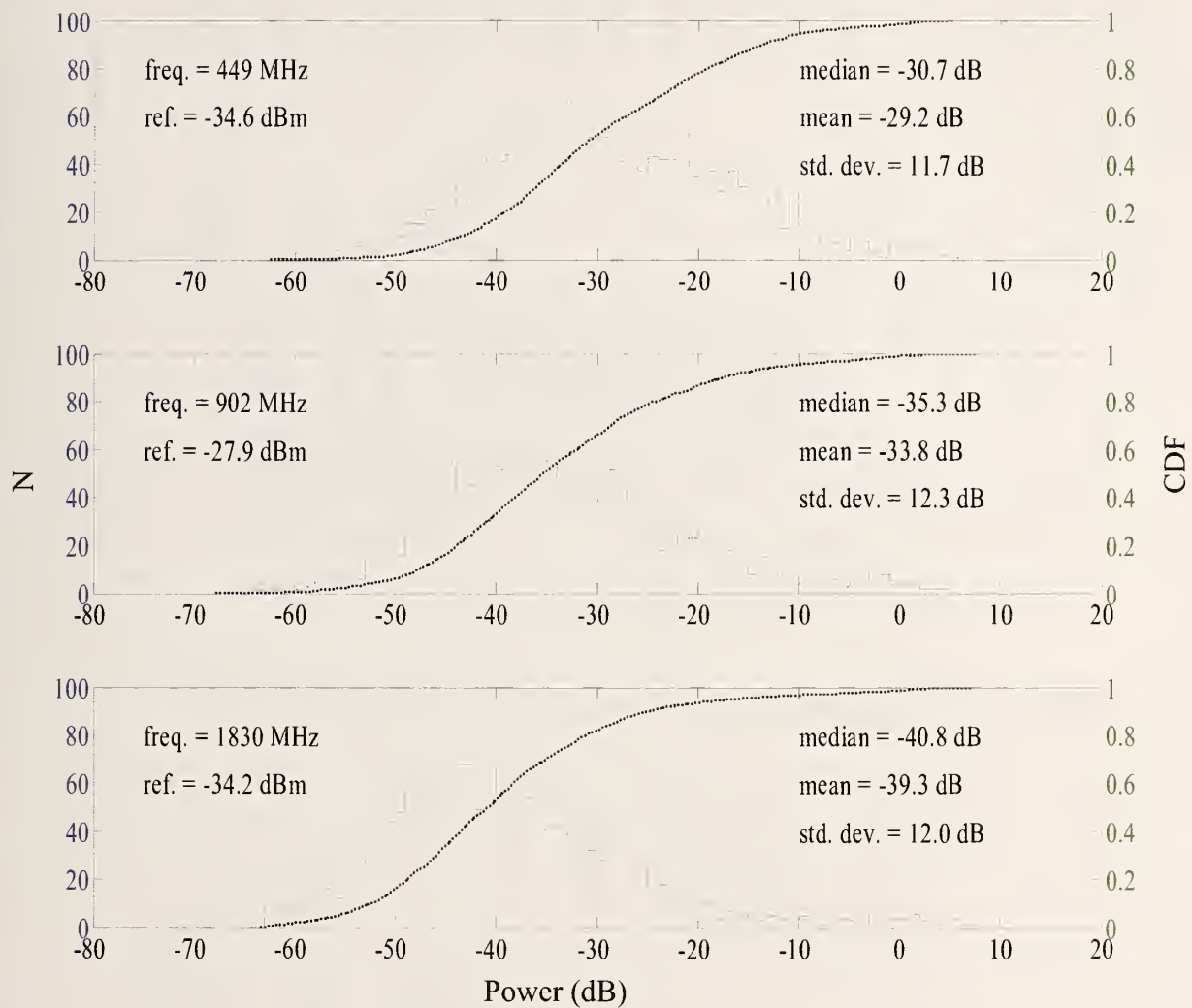


Figure 137. Boulder, CO grocery store statistics, histograms, and empirical CDF for walk-through data; 448.50, 902.75, and 1830.00 MHz.

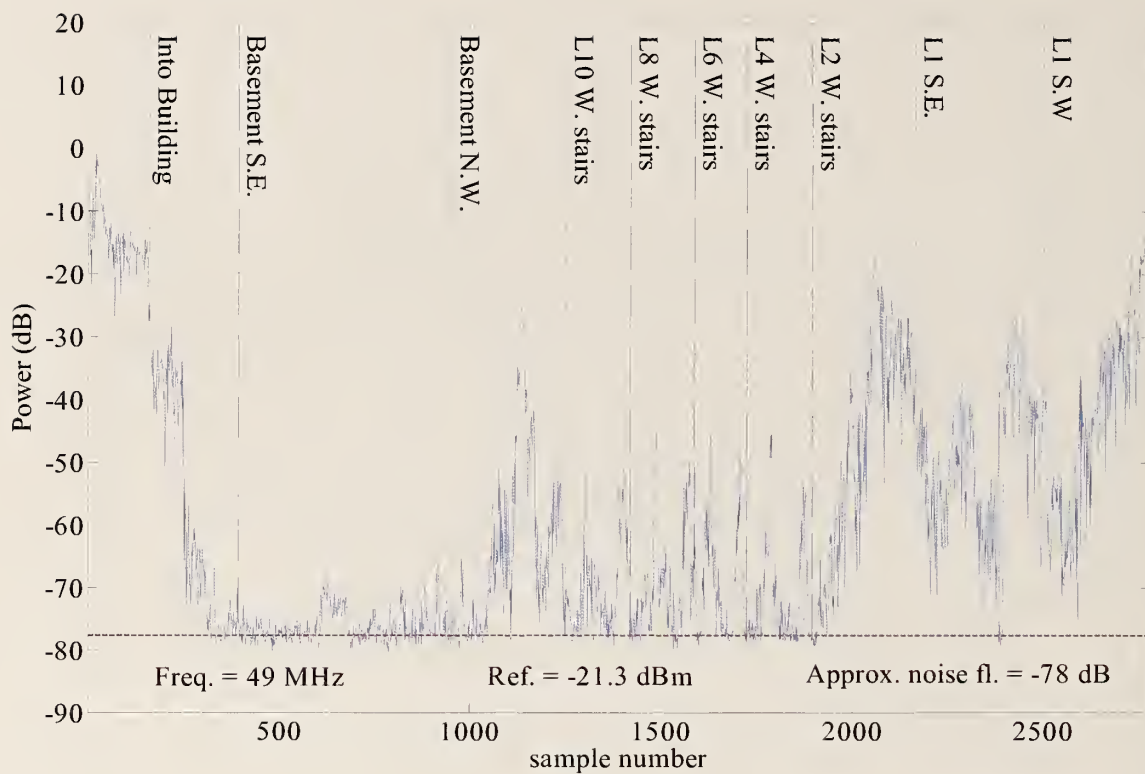


Figure 138. Gaithersburg, MD office building walk-through at 49.60 MHz.

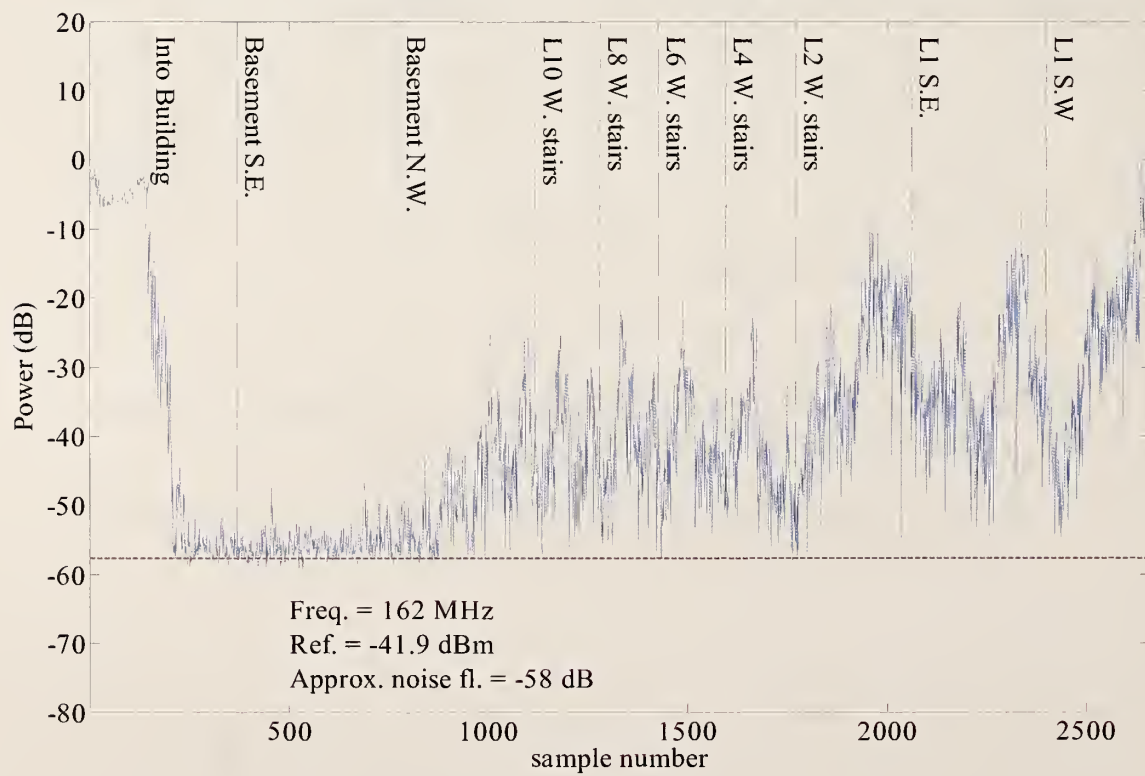


Figure 139. Gaithersburg, MD office building walk-through at 162.09 MHz.



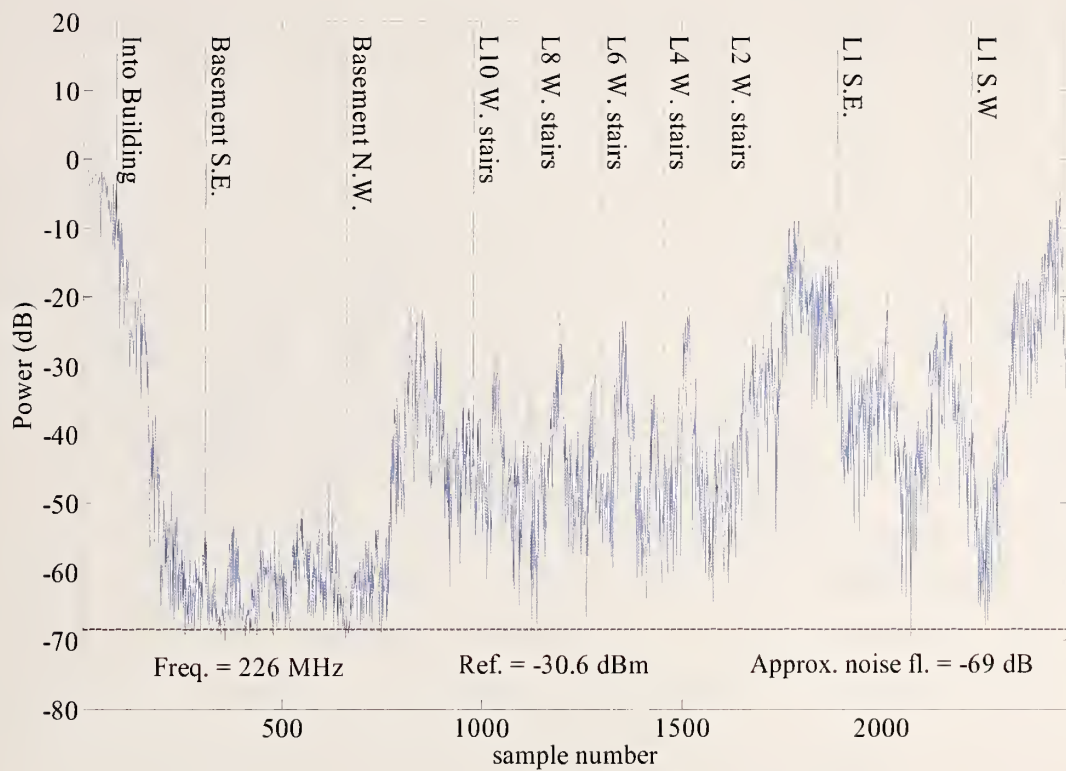


Figure 140. Gaithersburg, MD office building walk-through at 226.40 MHz.

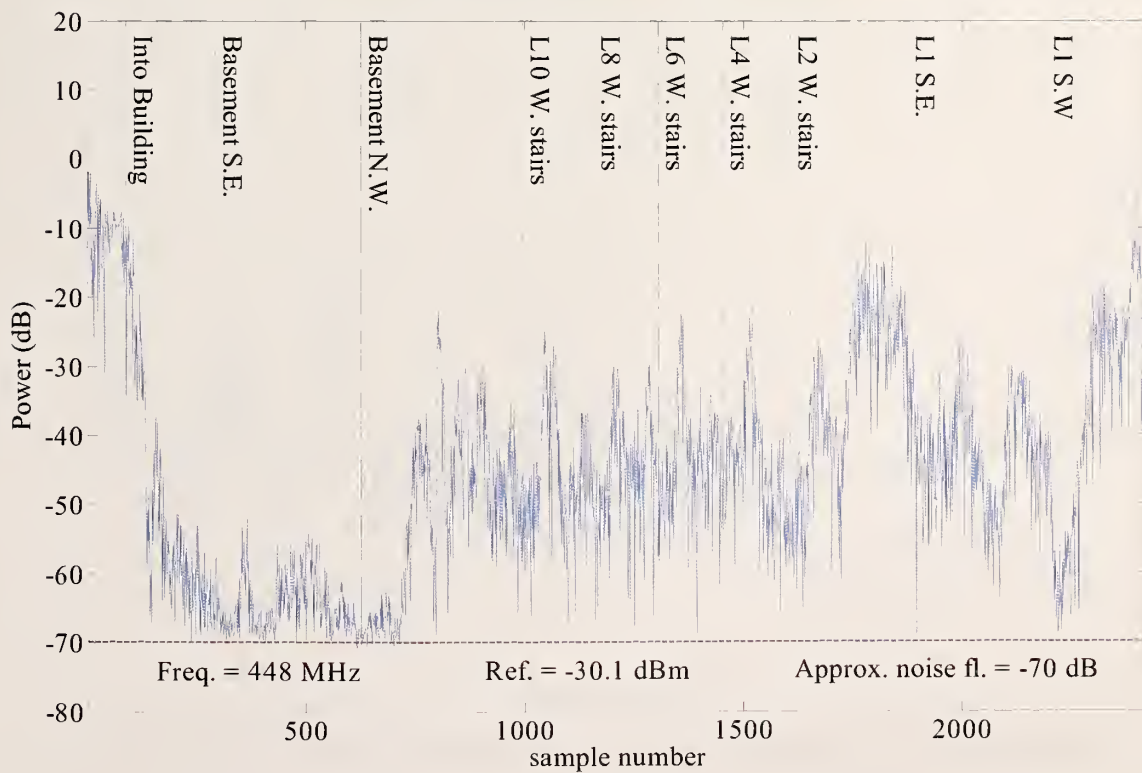


Figure 141. Gaithersburg, MD office building walk-through at 448.30 MHz.

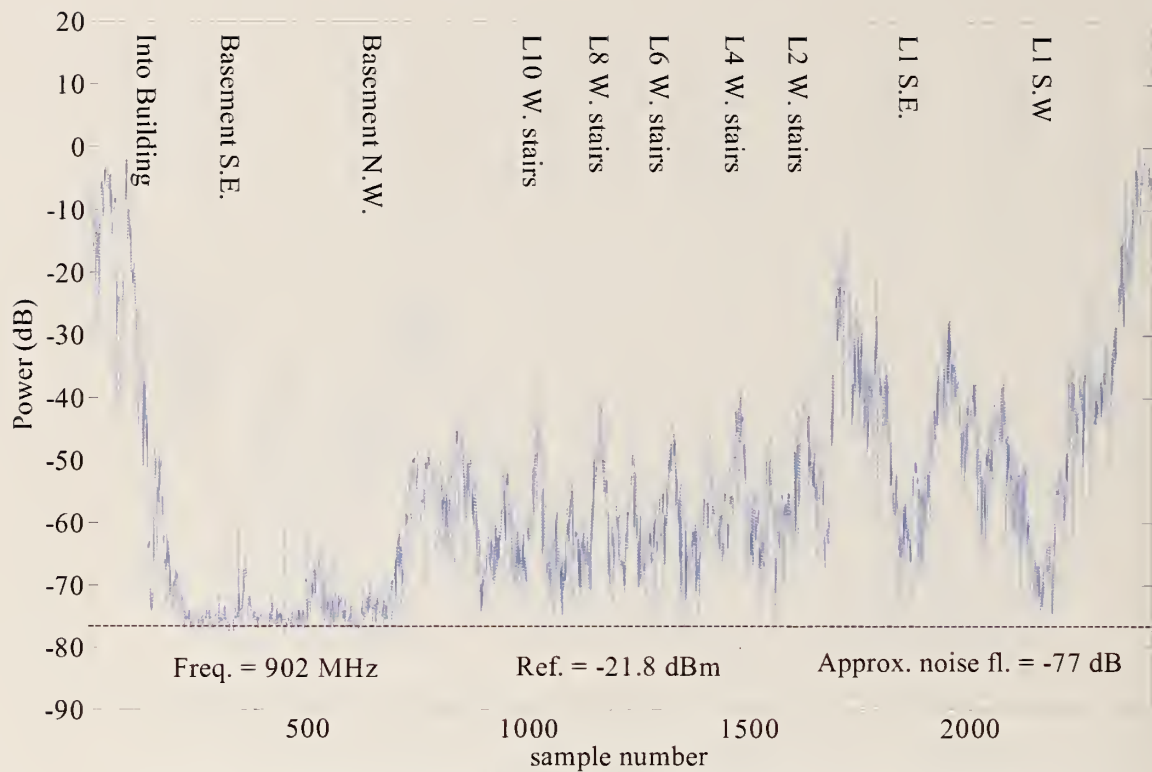


Figure 142. Gaithersburg, MD office building walk-through at 902.45 MHz.

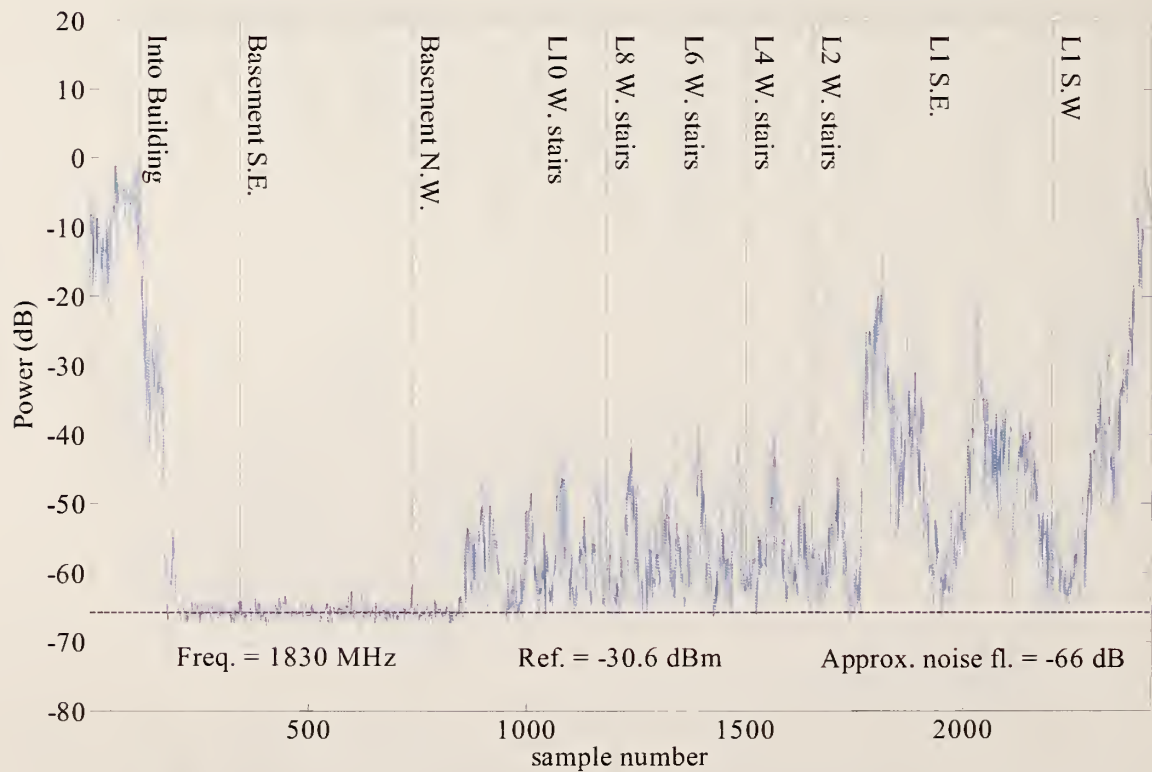


Figure 143. Gaithersburg, MD office building walk-through at 1830.00 MHz.

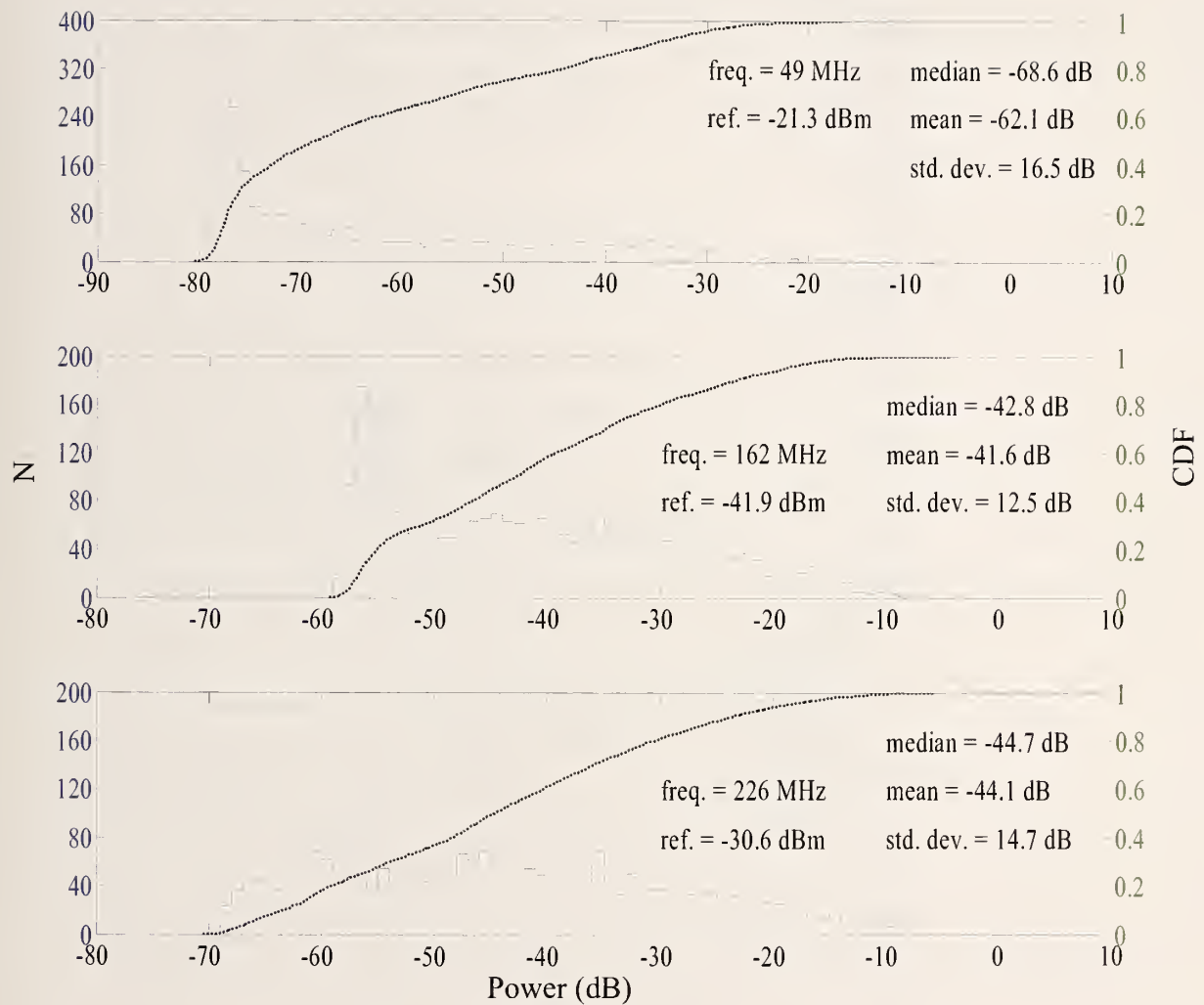


Figure 144. Gaithersburg, MD office building statistics, histograms, and empirical CDF for walk-through data; 49.60, 162.09, and 226.40 MHz.



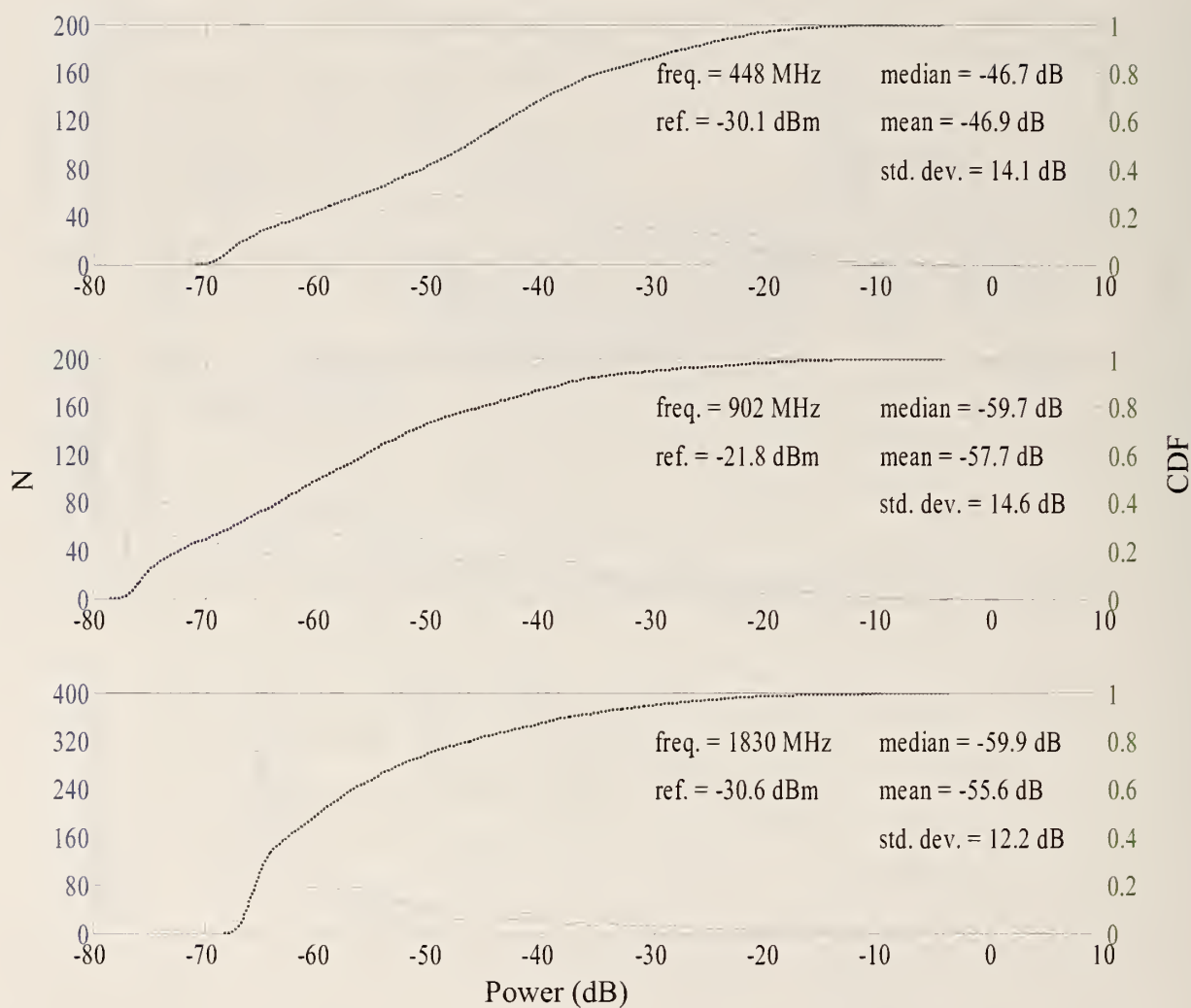


Figure 145. Gaithersburg, MD office building statistics, histograms, and empirical CDF for walk-through data; 448.30, 902.45, and 1830.00 MHz.

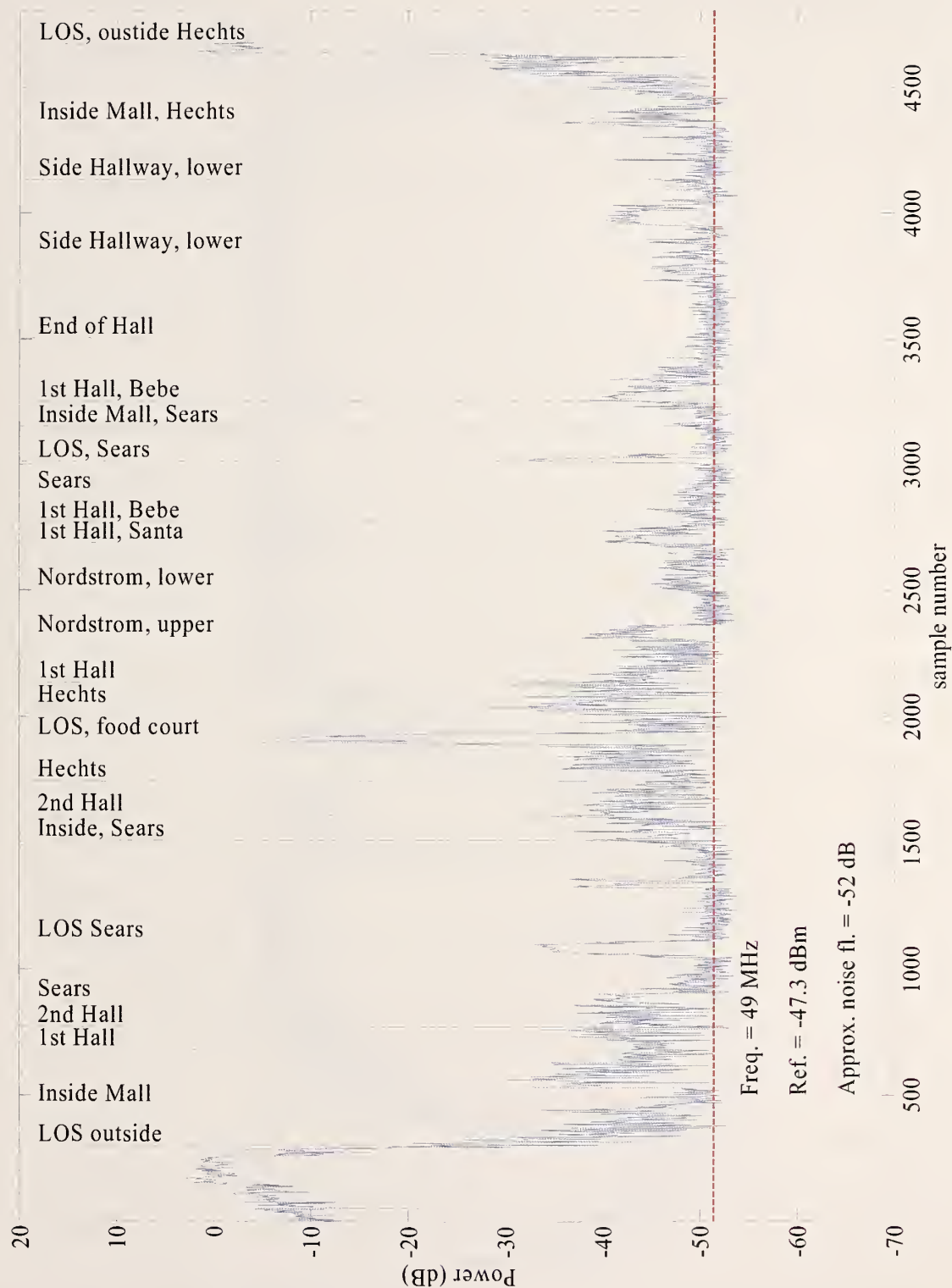


Figure 146. Bethesda, MD shopping mall walk-through at 49.60 MHz; receiver at site 1.

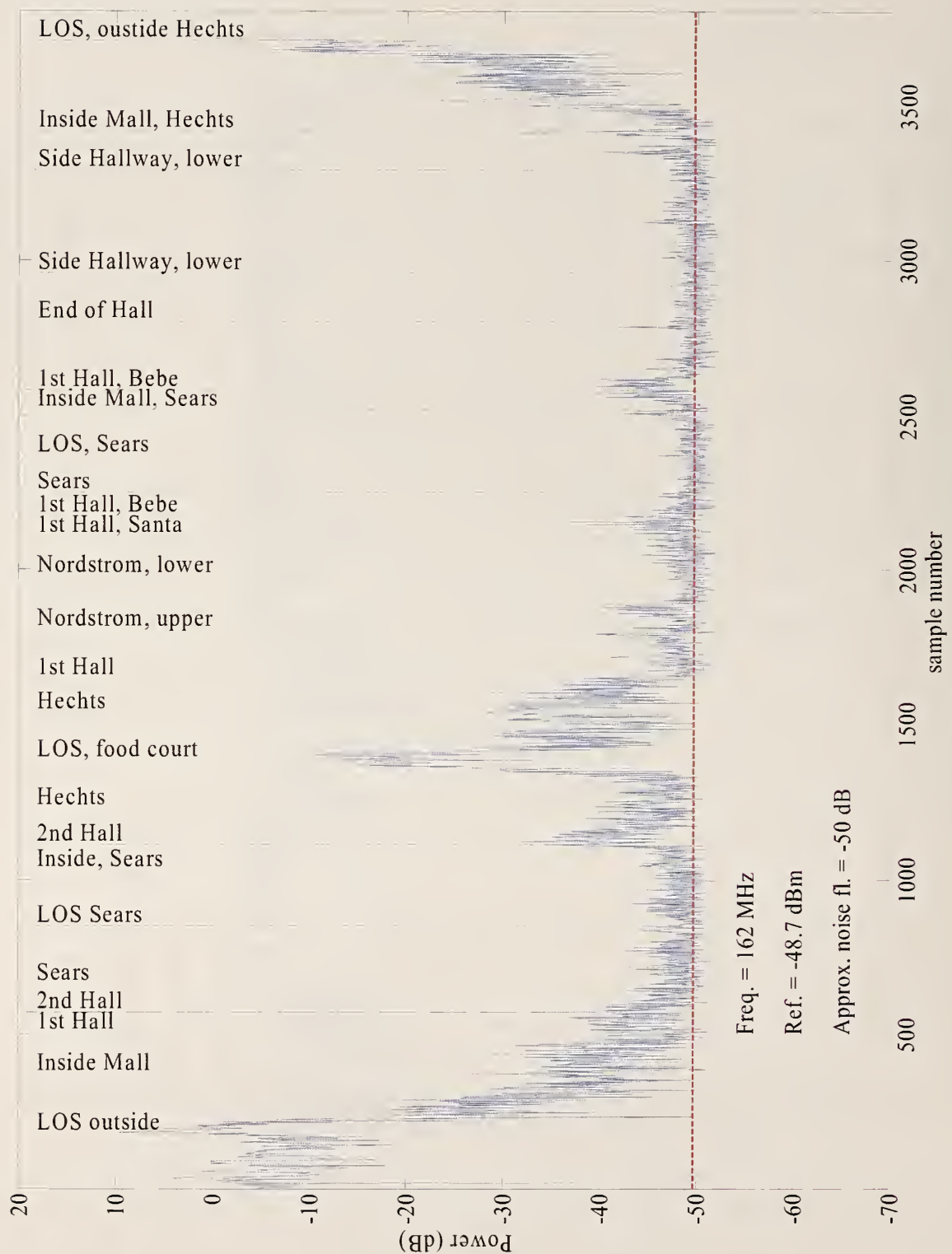


Figure 147. Bethesda, MD shopping mall walk-through at 162.09 MHz; receiver at site 1.





Figure 148. Bethesda, MD shopping mall walk-through at 226.40 MHz; receiver at site 1.

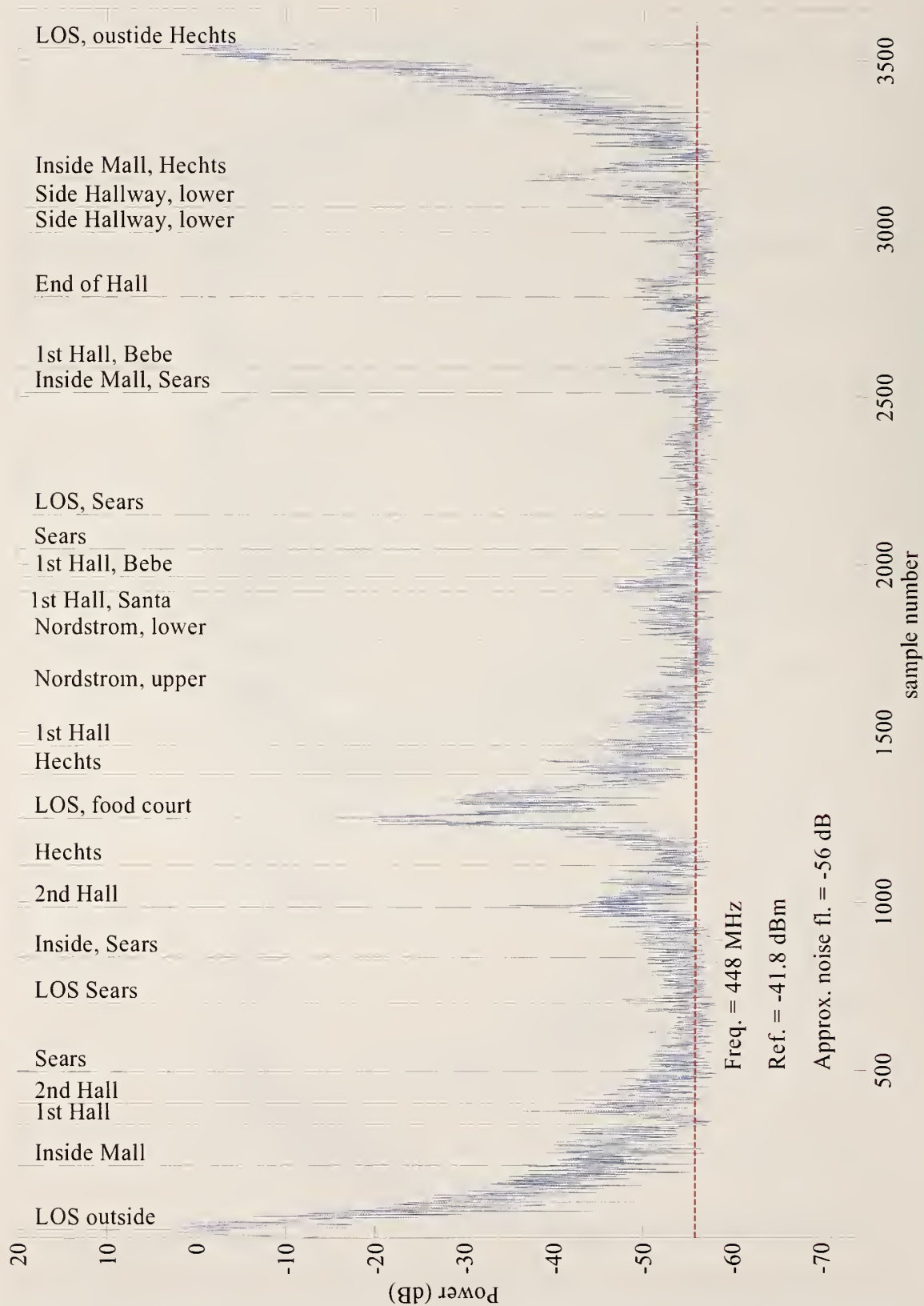


Figure 149. Bethesda, MD shopping mall walk-through at 448.30 MHz; receiver at site 1.

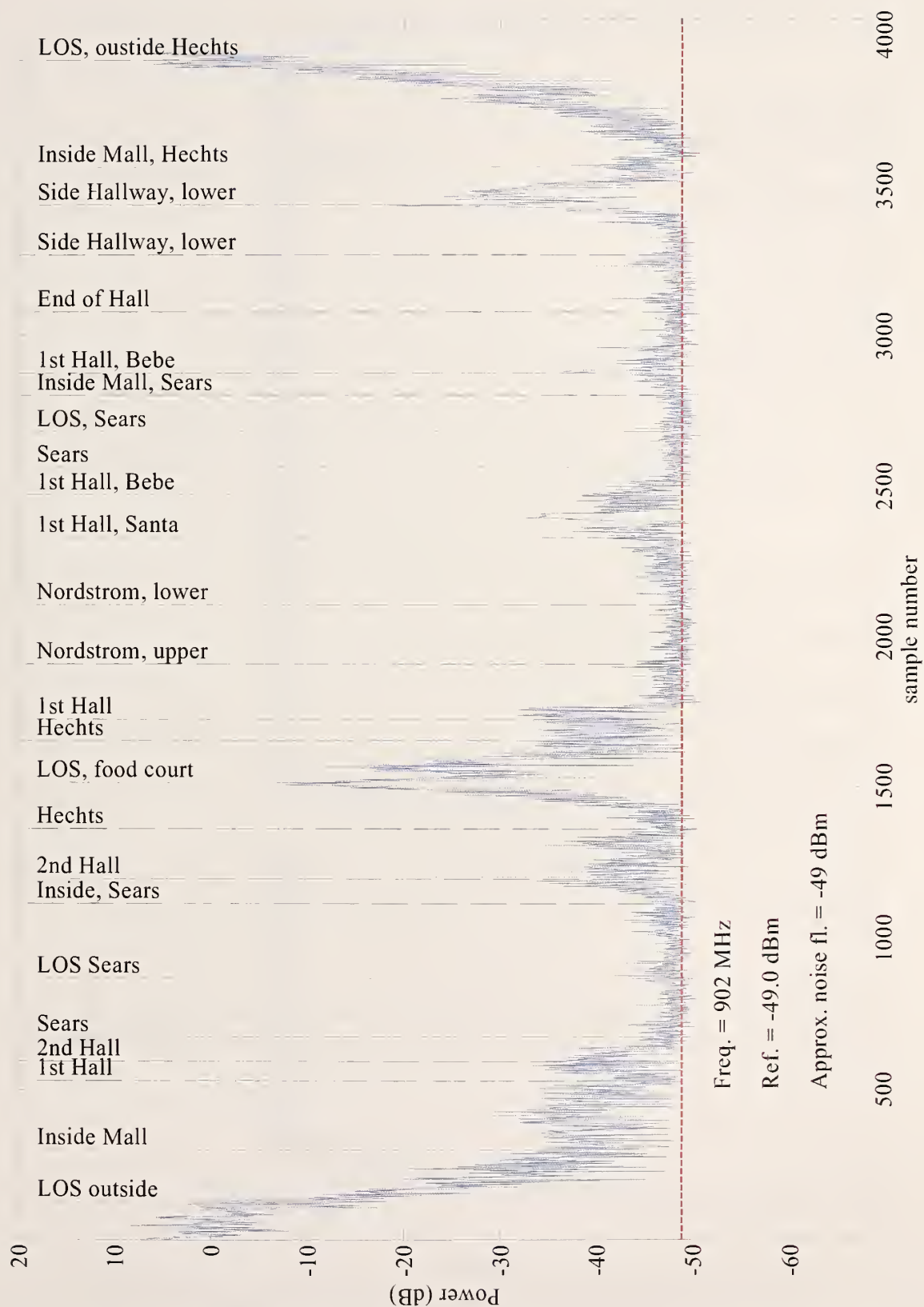


Figure 150. Bethesda, MD shopping mall walk-through at 902.45 MHz; receiver at site 1.





Figure 151. Bethesda, MD shopping mall walk-through at 1830.00 MHz;  
receiver at site 1.

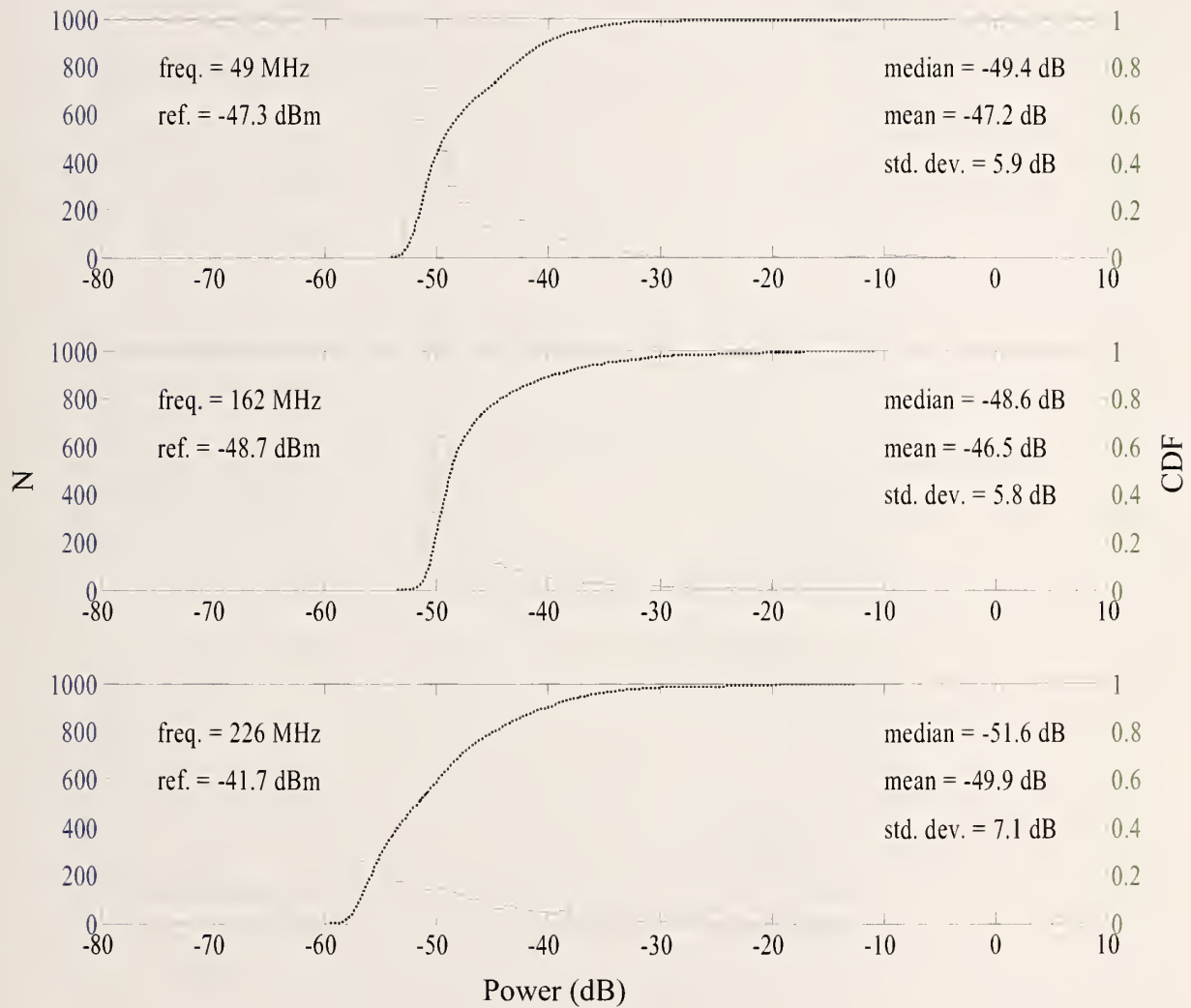


Figure 152. Bethesda, MD shopping mall statistics, histograms, and empirical CDF for walk-through data with the receiver at site 1; 49.60, 162.09, and 226.40 MHz.

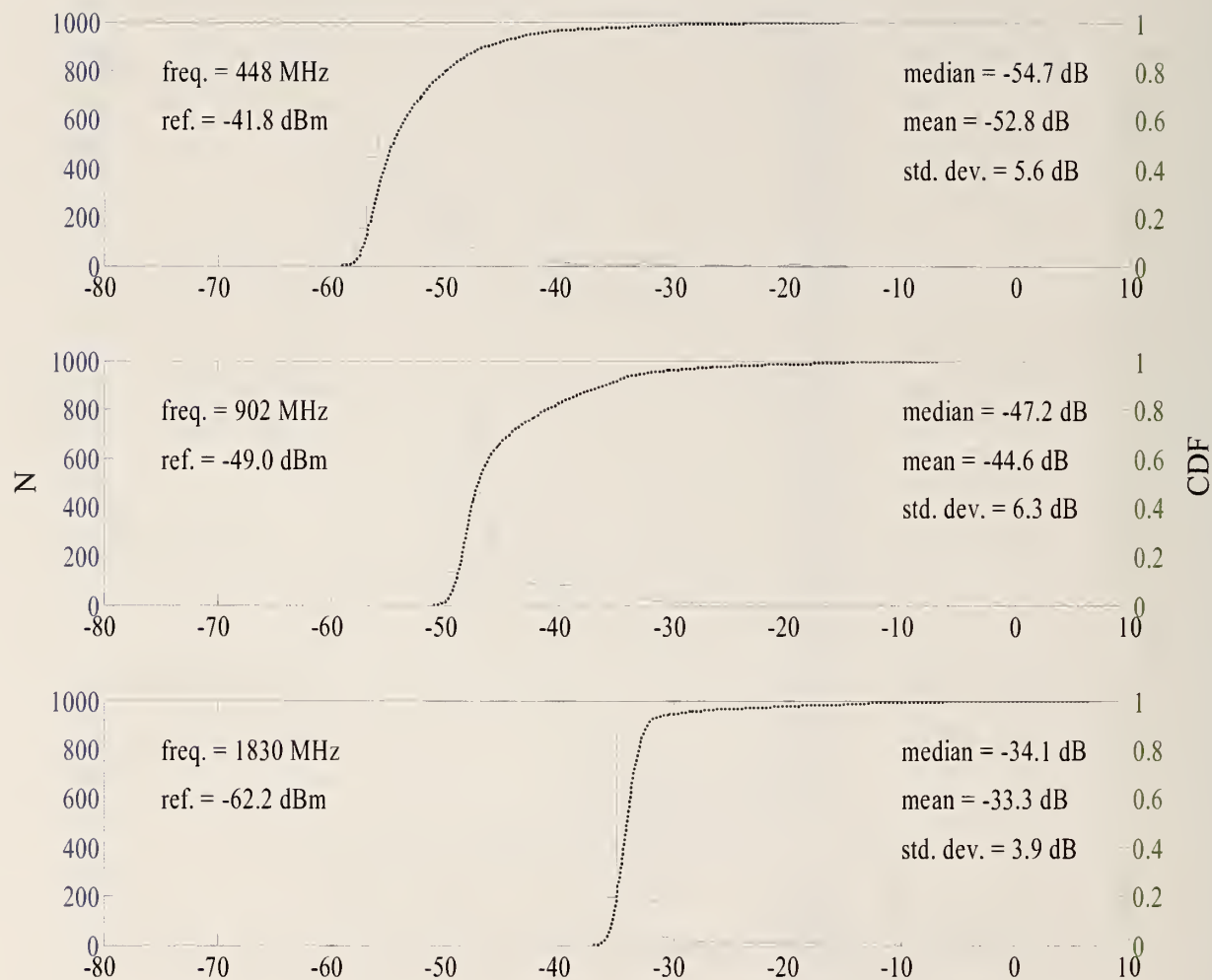


Figure 153. Bethesda, MD shopping mall statistics, histograms, and empirical CDF for walk-through data with the receiver at site 1; 448.30, 902.45, and 1830.00 MHz.



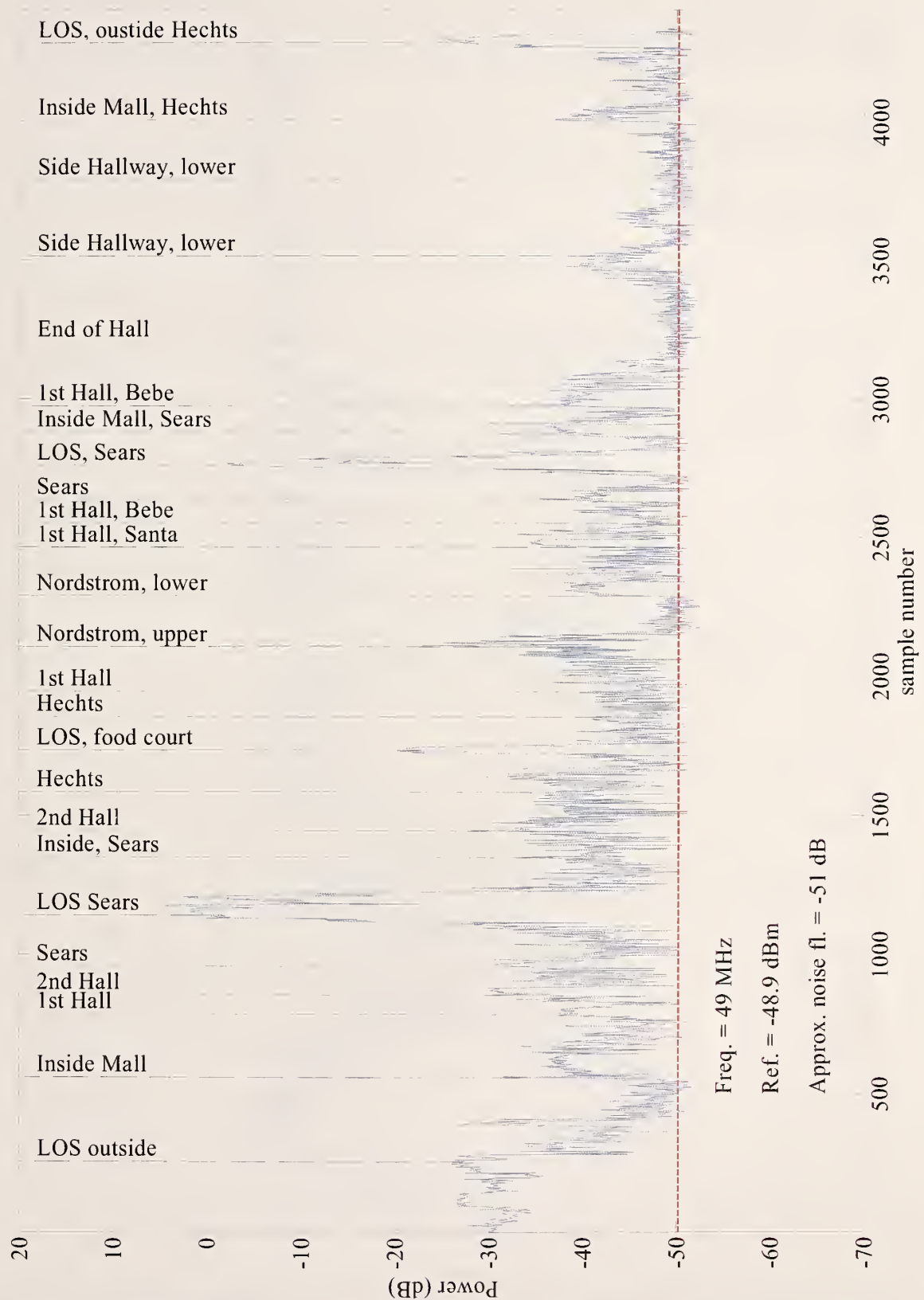


Figure 154. Bethesda, MD shopping mall walk-through at 49.60 MHz; receiver at site 2.



Figure 155. Bethesda, MD shopping mall walk-through at 162.09 MHz; receiver at site 2.



Figure 156. Bethesda, MD shopping mall walk-through at 226.40 MHz; receiver at site 2.



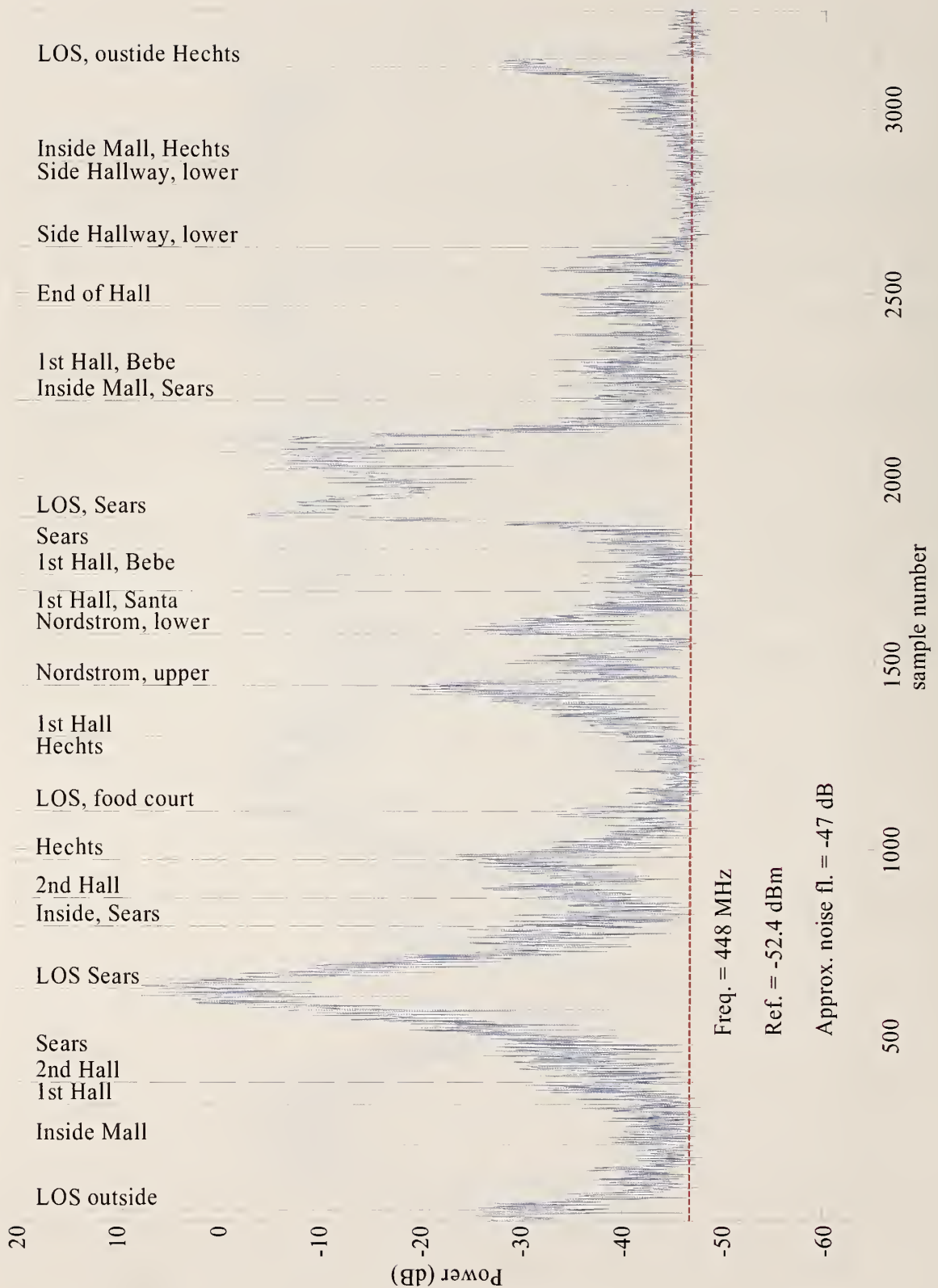


Figure 157. Bethesda, MD shopping mall walk-through at 448.30 MHz; receiver at site 2.



Figure 158. Bethesda, MD shopping mall walk-through at 902.45 MHz; receiver at site 2.

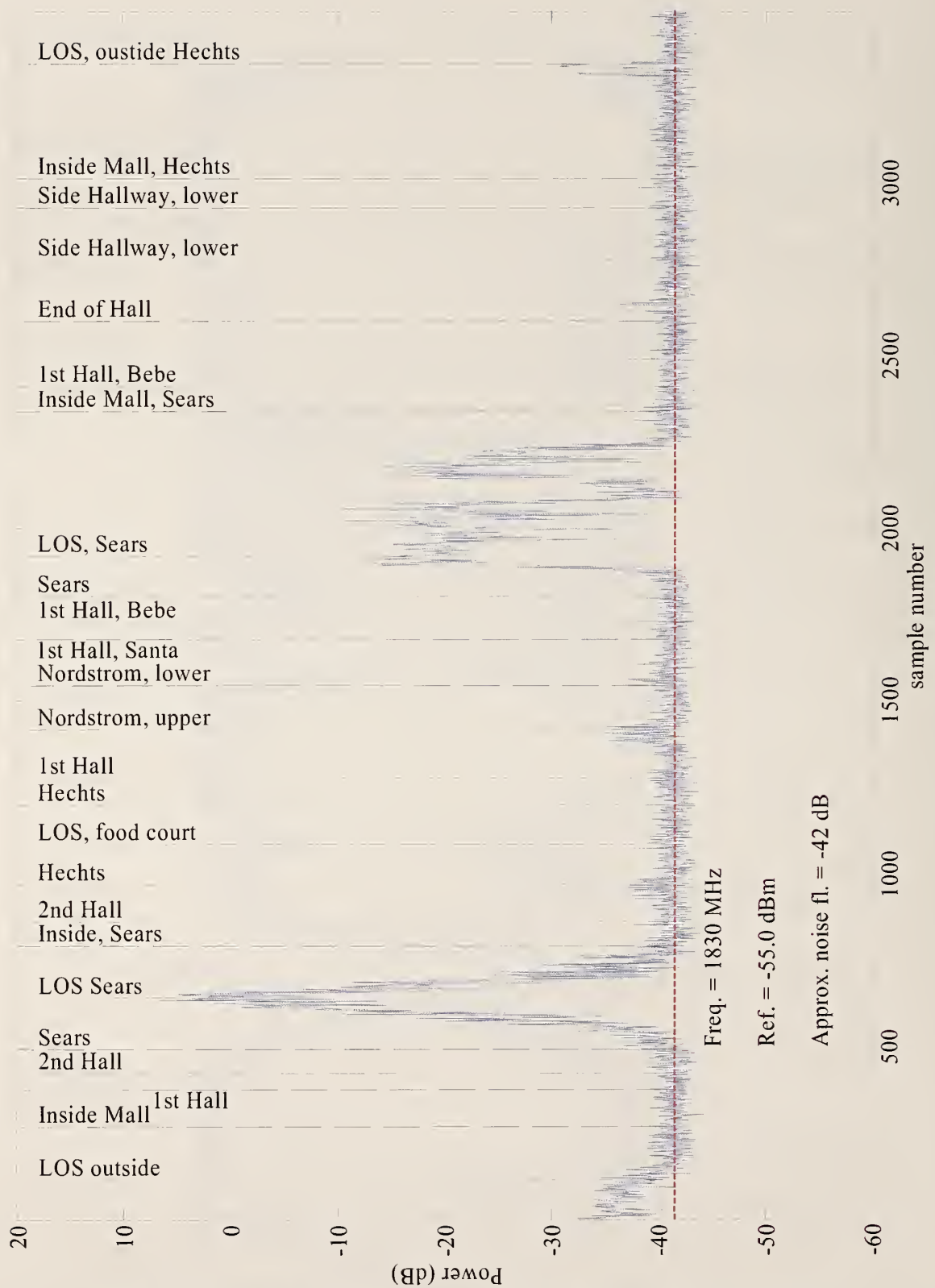


Figure 159. Bethesda, MD shopping mall walk-through at 1830.00 MHz;  
receiver at site 2.



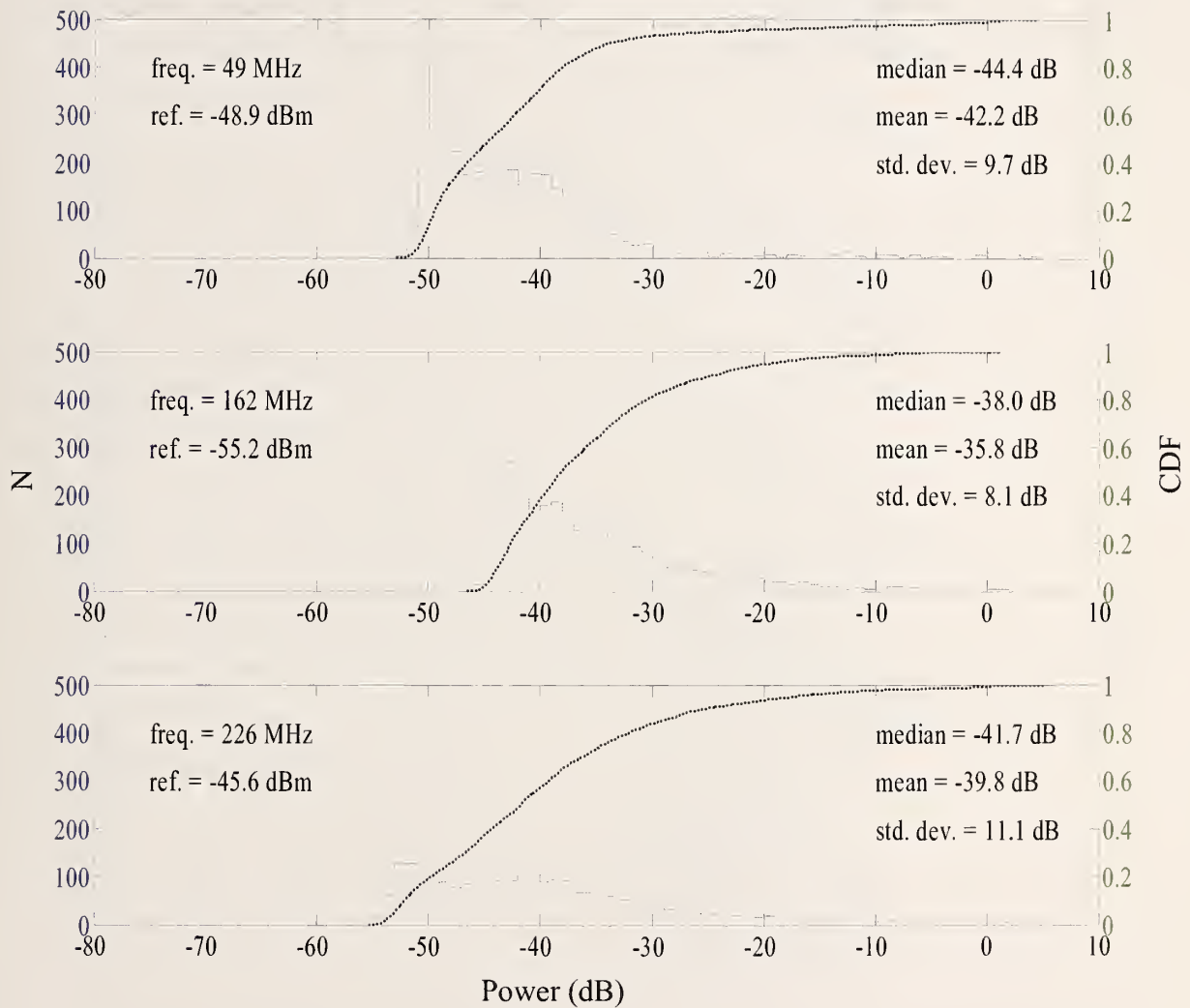


Figure 160. Bethesda, MD shopping mall statistics, histograms, and empirical CDF for walk-through data with the receiver at site 2; 49.60, 162.09, and 226.40 MHz.

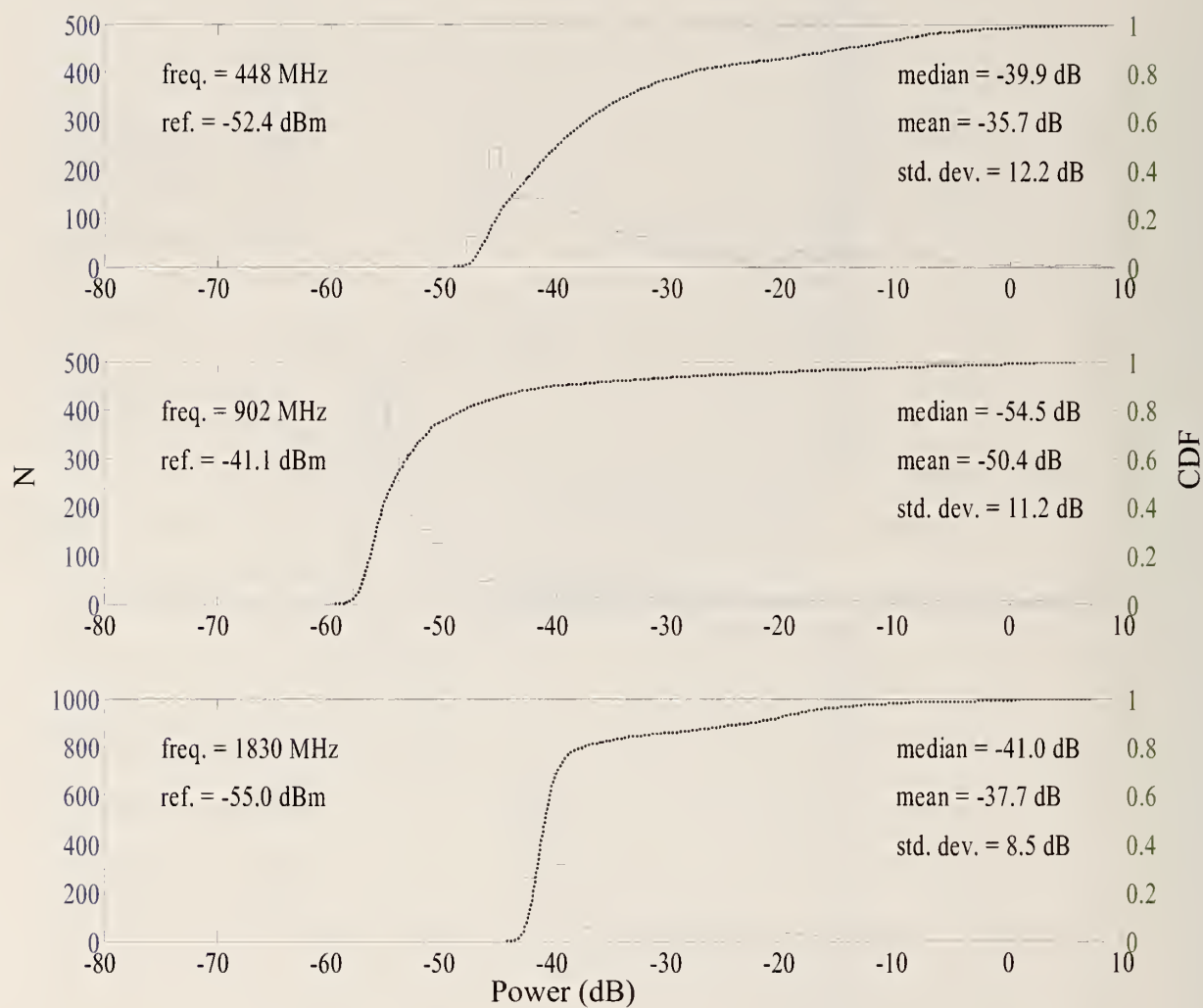


Figure 161. Bethesda, MD shopping mall statistics, histograms, and empirical CDF for walk-through data with the receiver at site 2; 448.30, 902.45, and 1830.00 MHz.



Figure 162. Silver Spring, MD office building walk-through at 49.60 MHz.



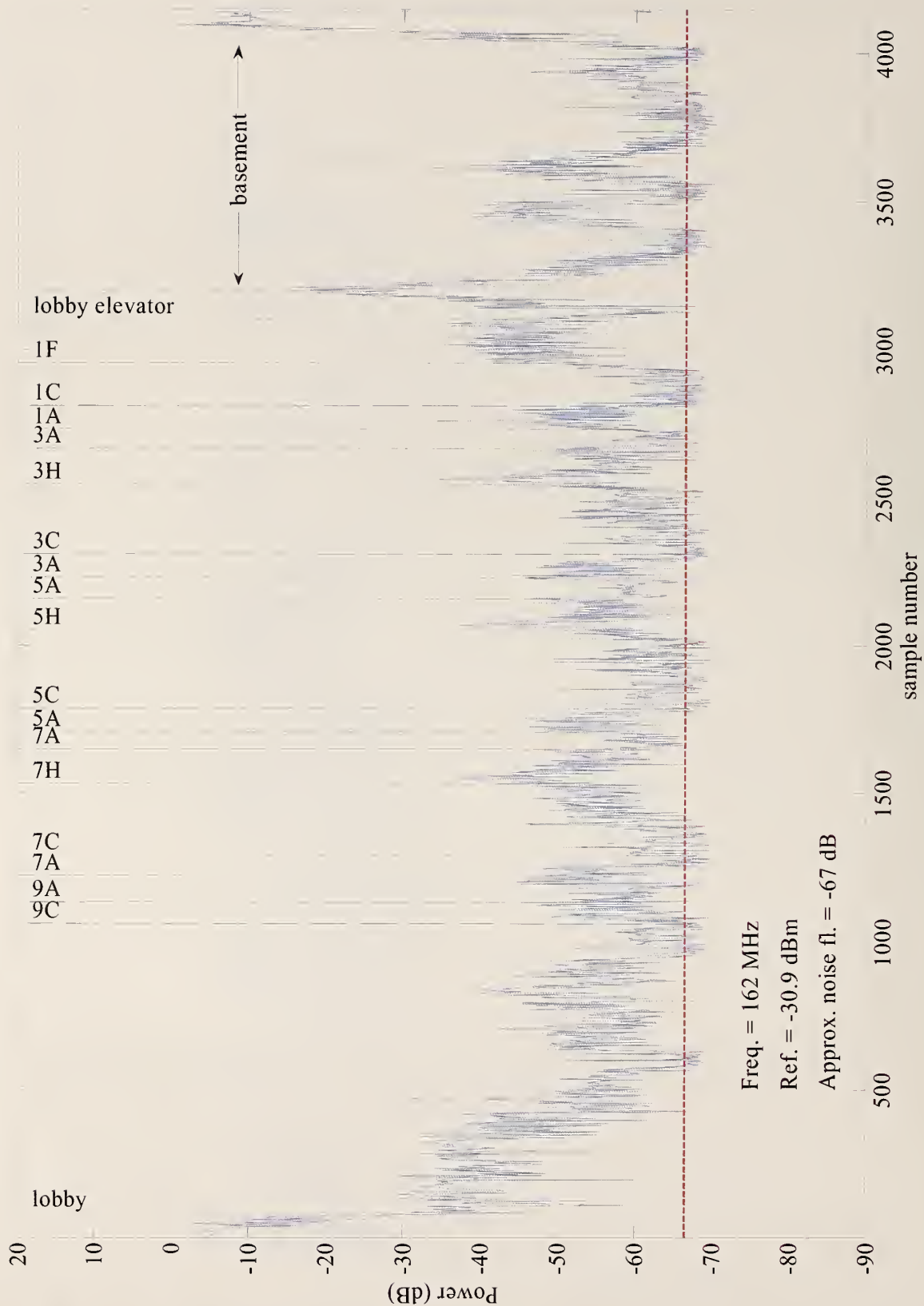


Figure 163. Silver Spring, MD office building walk-through at 162.09 MHz.

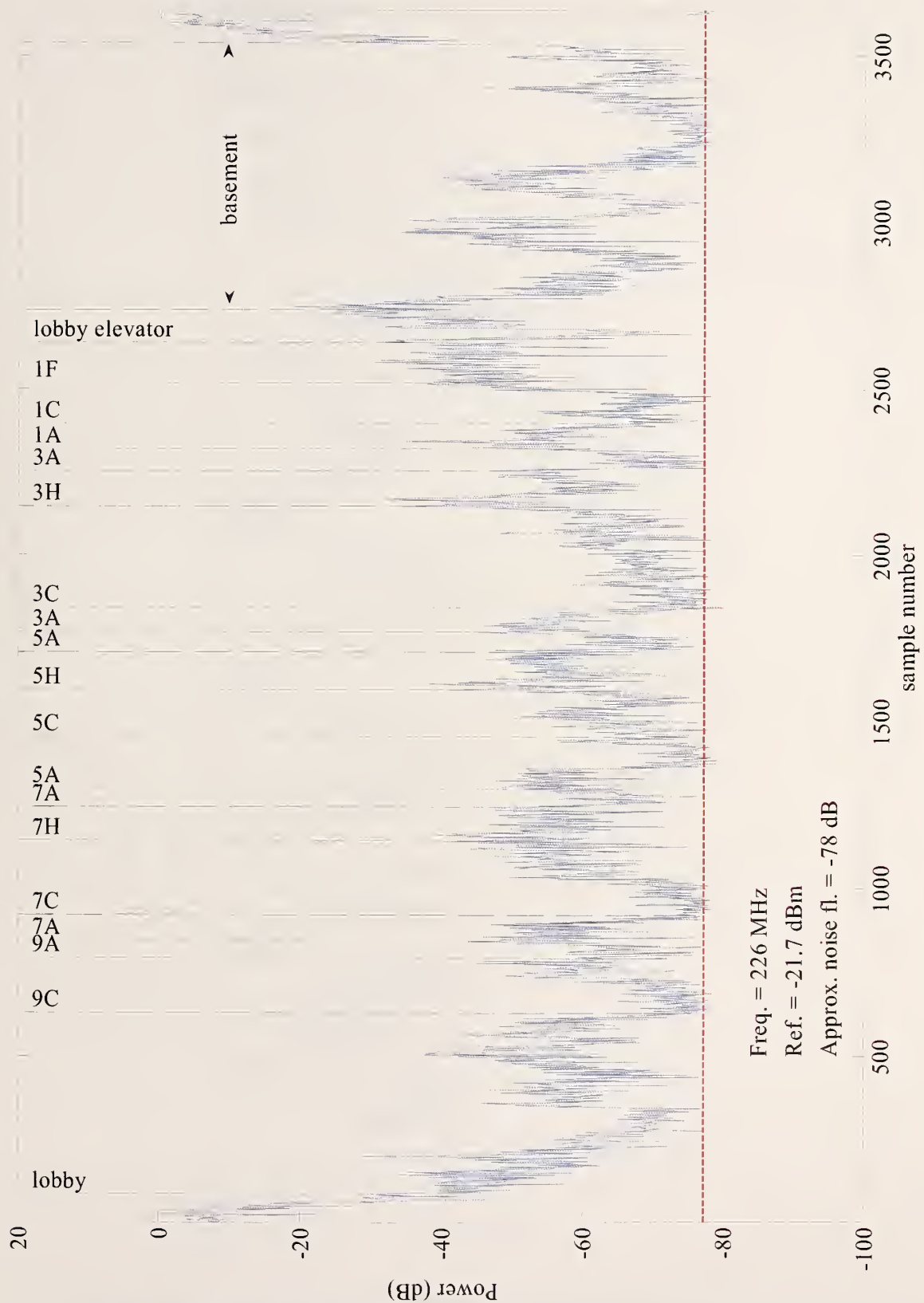


Figure 164. Silver Spring, MD office building walk-through at 226.40 MHz.

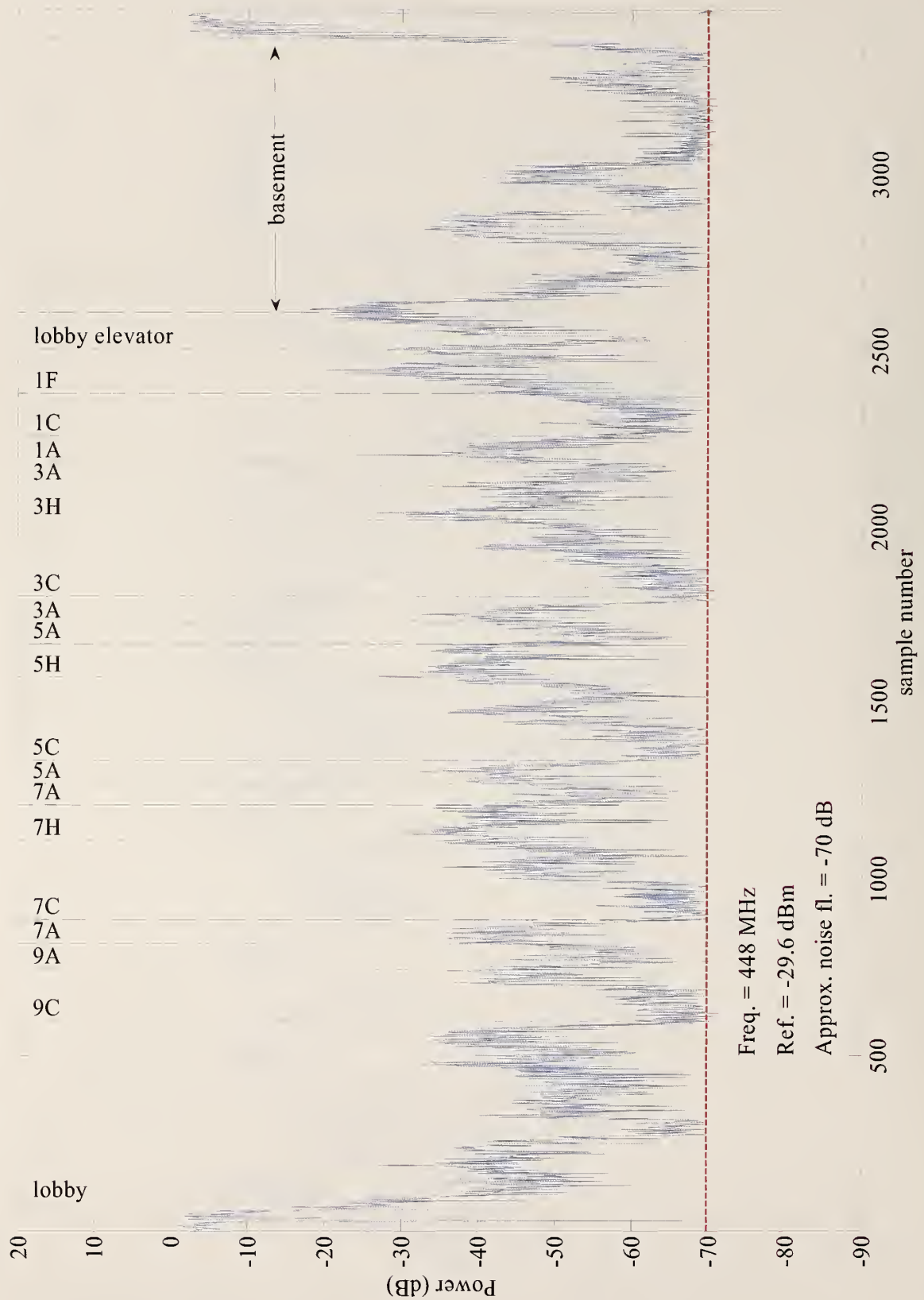


Figure 165. Silver Spring, MD office building walk-through at 448.30 MHz.



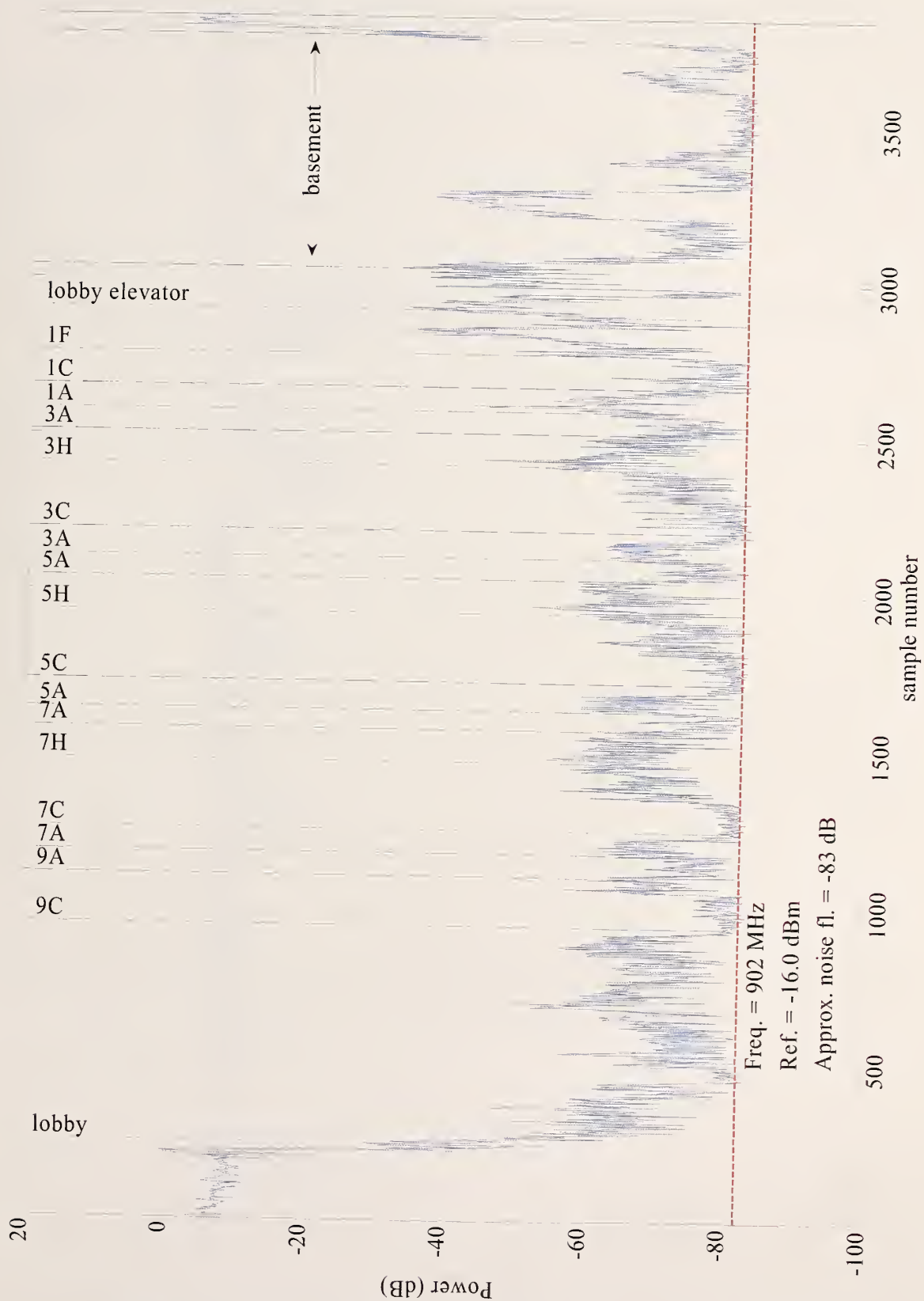


Figure 166. Silver Spring, MD office building walk-through at 902.45 MHz.

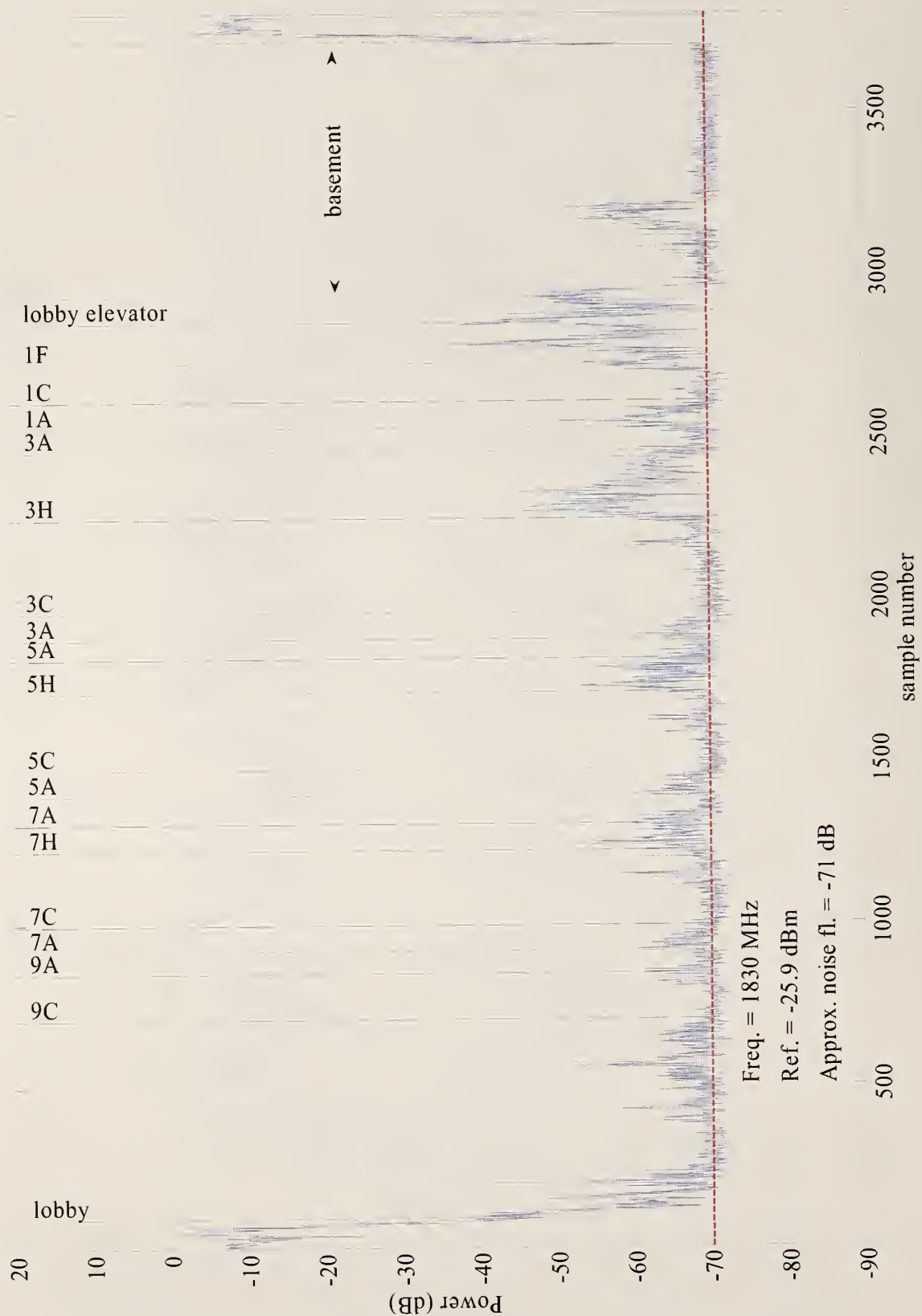


Figure 167. Silver Spring, MD office building walk-through at 1830.00 MHz.

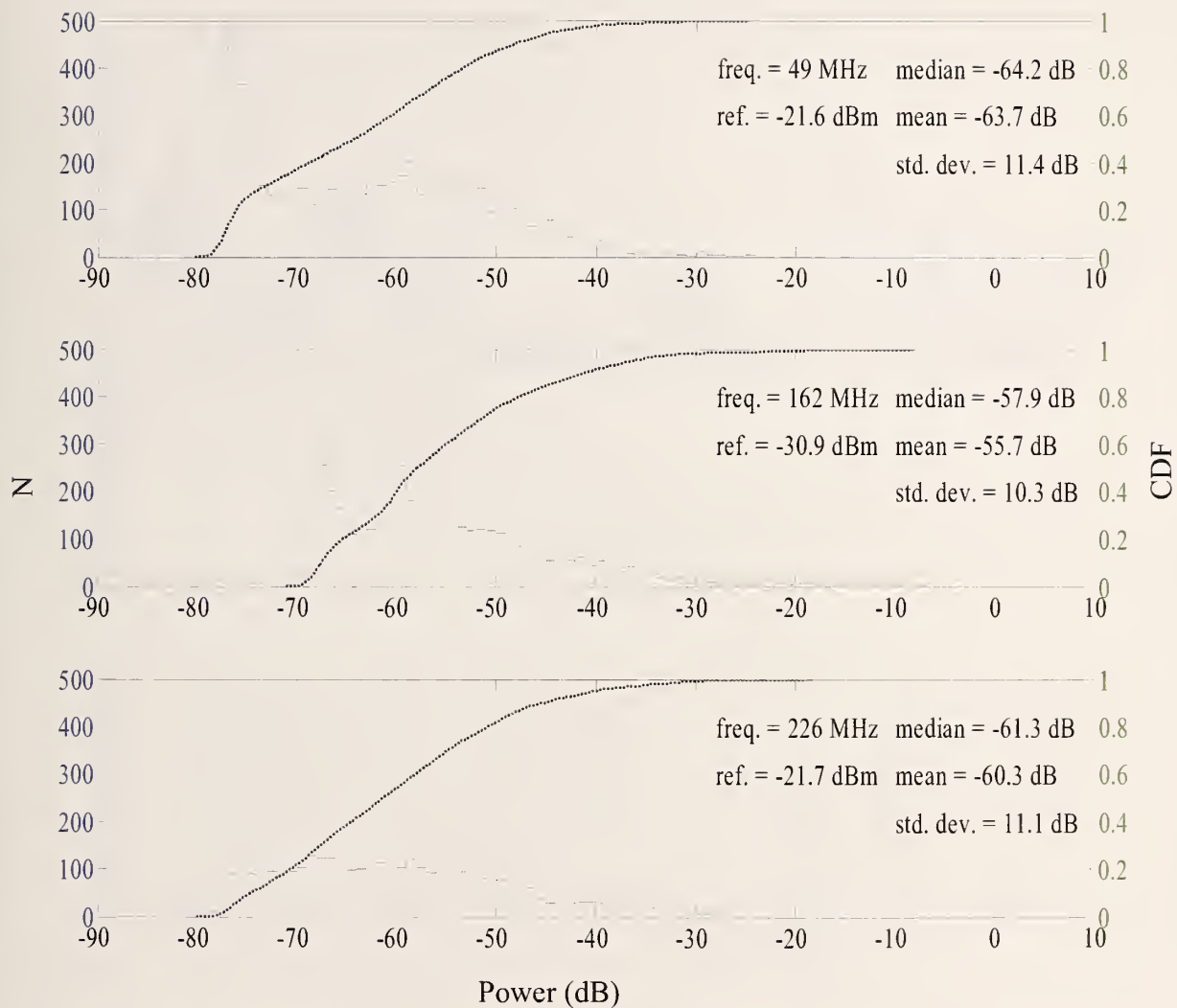


Figure 168. Silver Spring, MD office building statistics, histograms, and empirical CDF for walk-through data; 49.60, 162.09, and 226.40 MHz.



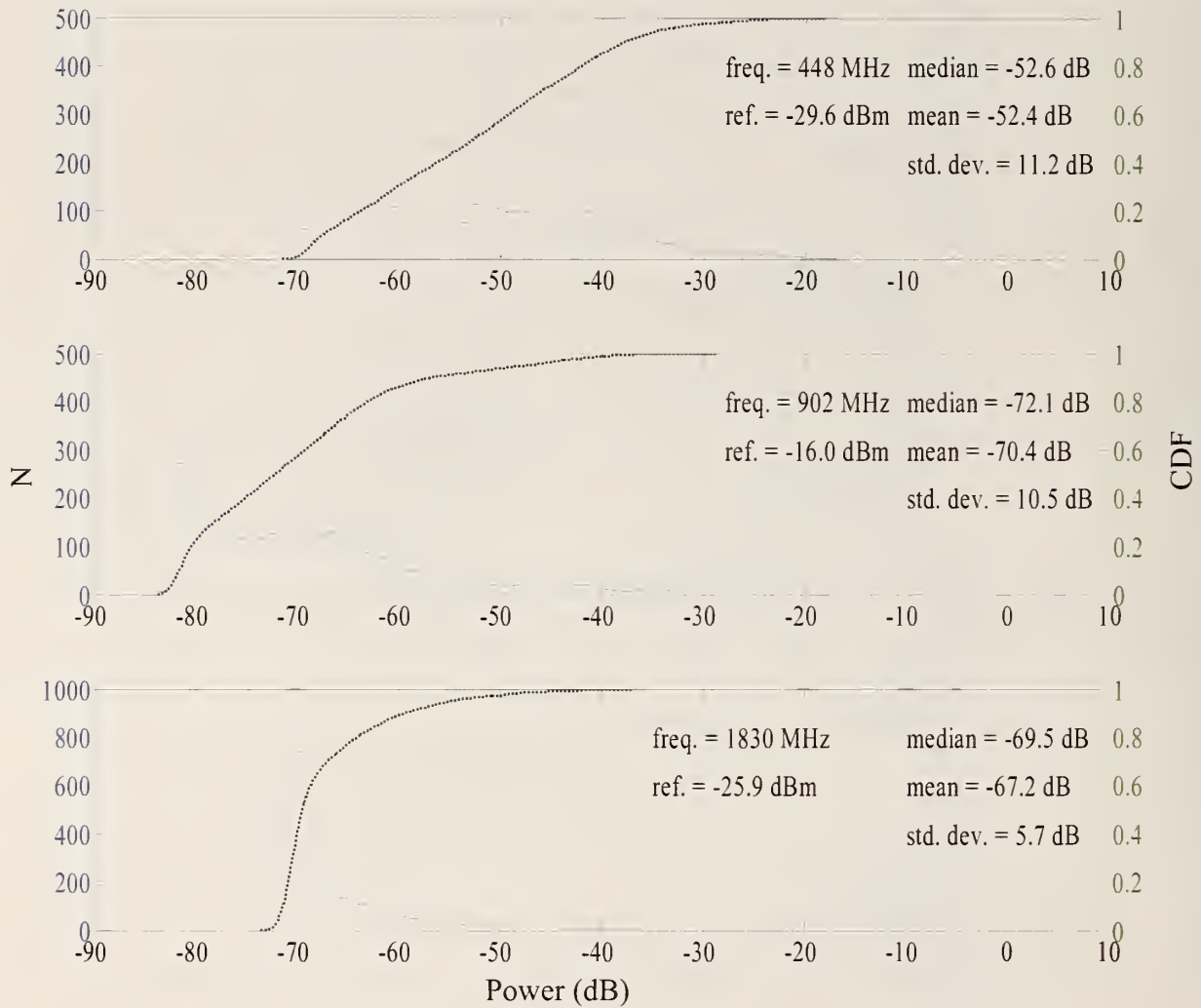


Figure 169. Silver Spring, MD office building statistics, histograms, and empirical CDF for walk-through data; 448.30, 902.45, and 1830.00 MHz.

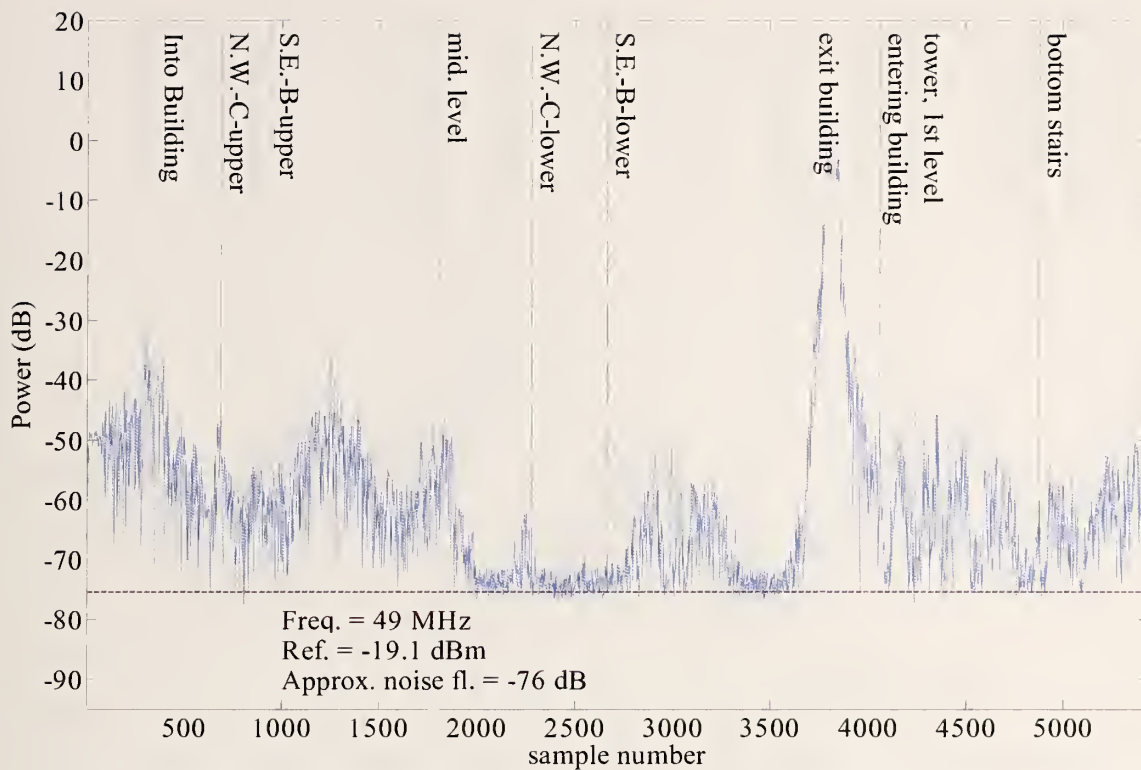


Figure 170. Washington, DC convention center walk-through at 49.60 MHz; receiver at site 1.

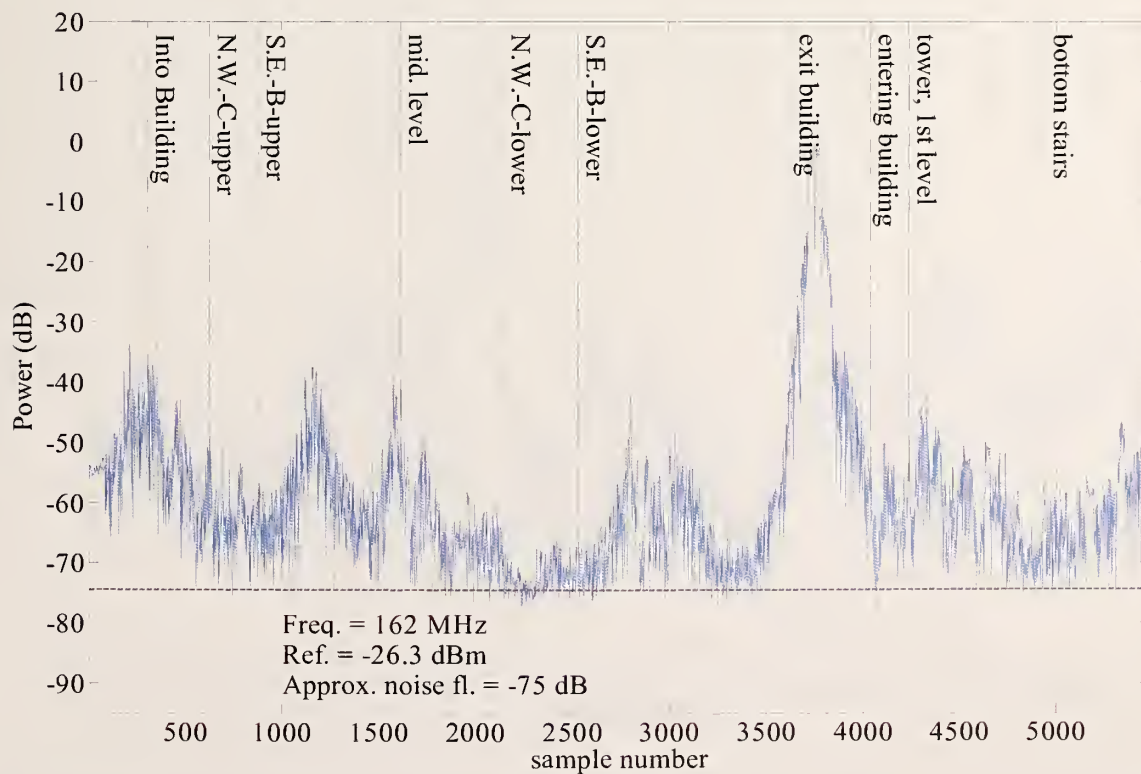


Figure 171. Washington, DC convention center walk-through at 162.09 MHz; receiver at site 1.

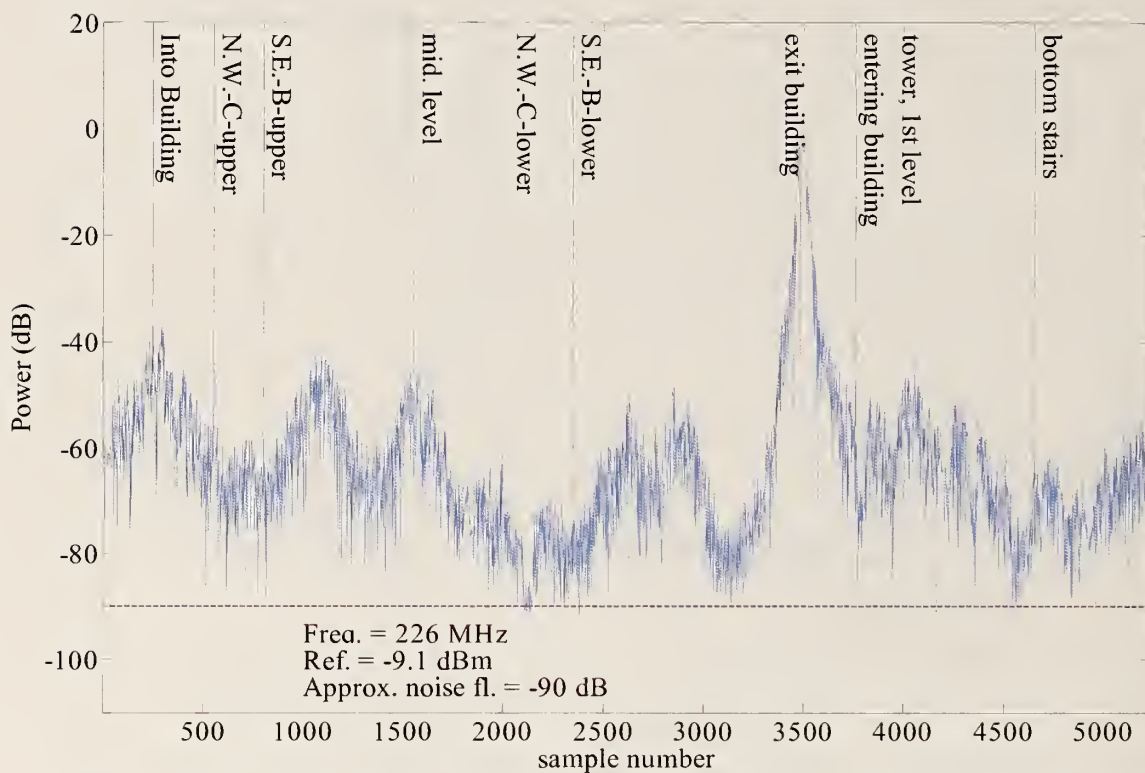


Figure 172. Washington, DC convention center walk-through at 226.40 MHz; receiver at site 1.

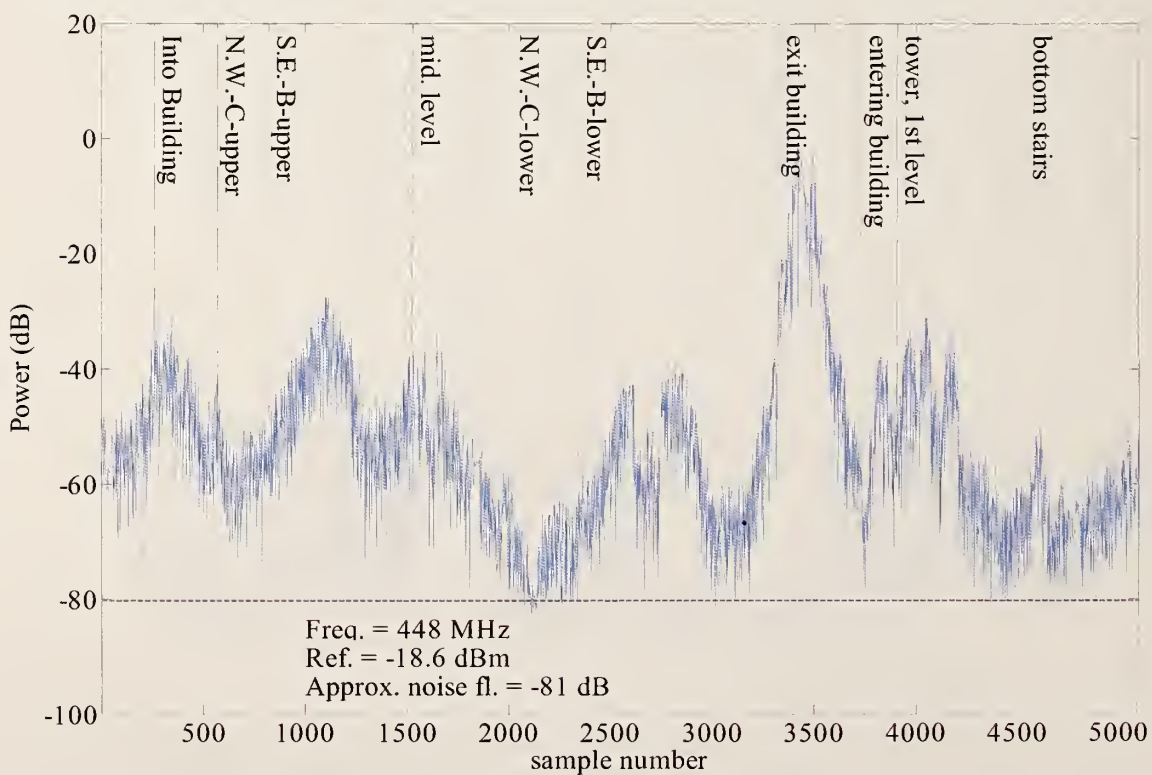


Figure 173. Washington, DC convention center walk-through at 448.30 MHz; receiver at site 1.



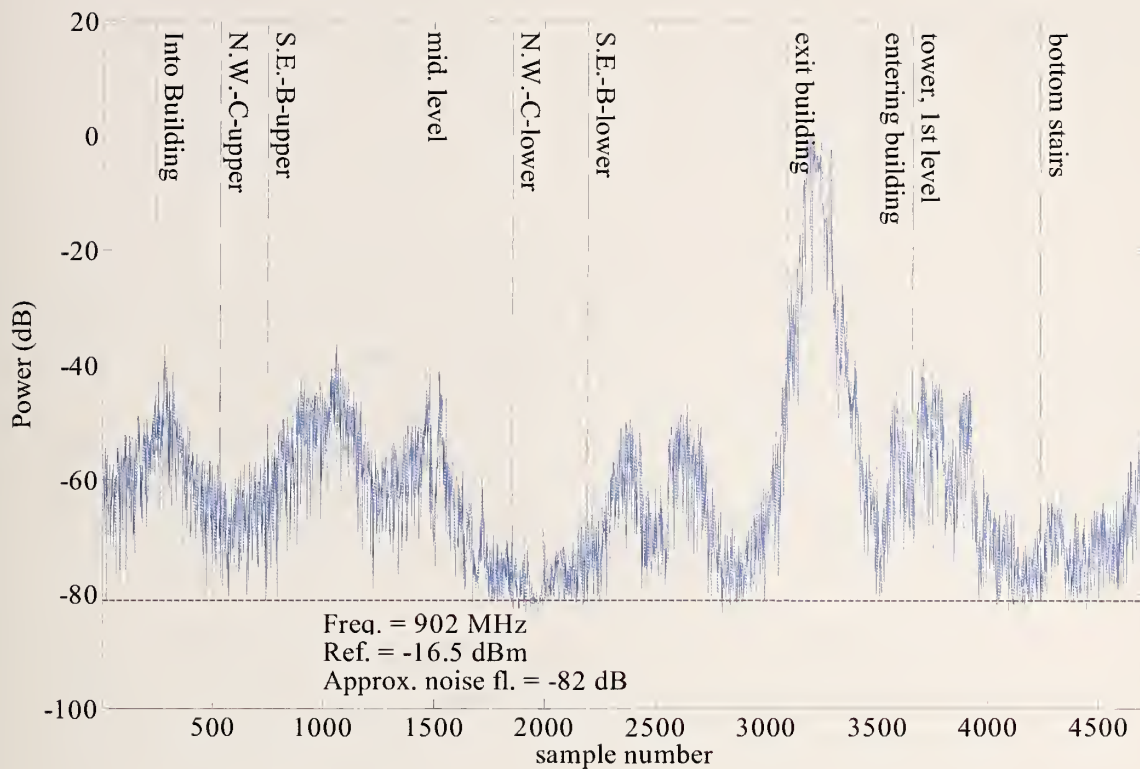


Figure 174. Washington, DC convention center walk-through at 902.45 MHz; receiver at site 1.

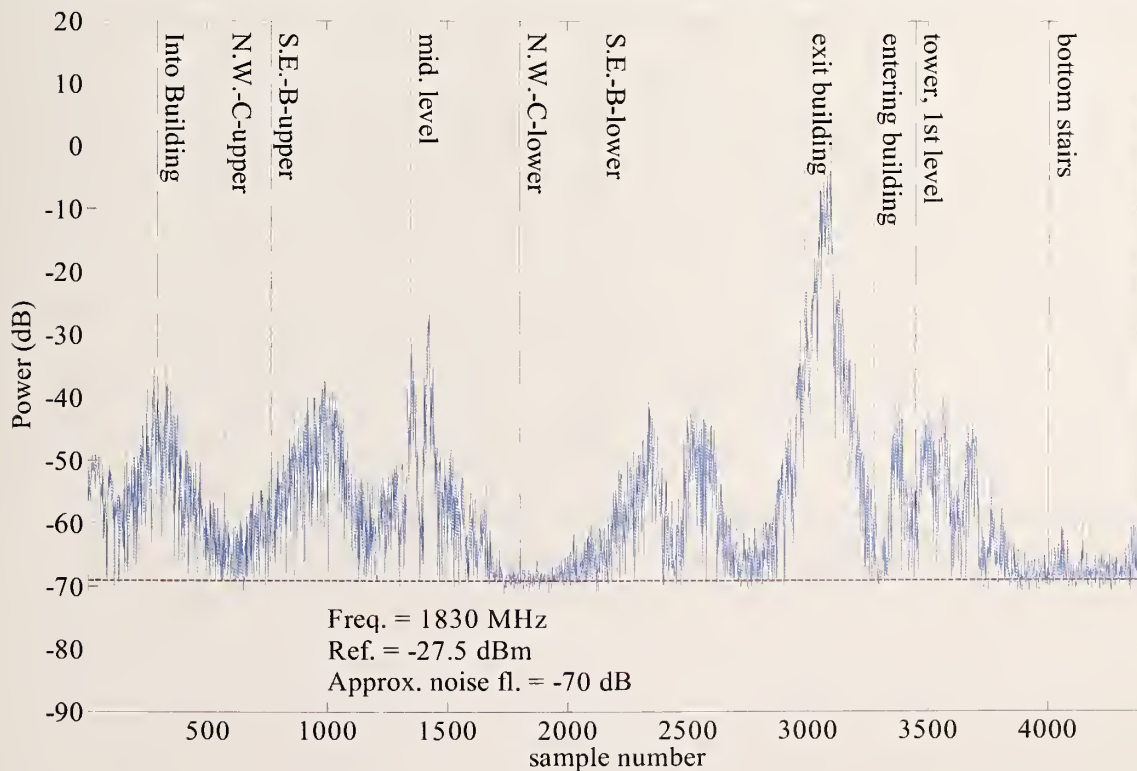


Figure 175. Washington, DC convention center walk-through at 1830.00 MHz; receiver at site 1.

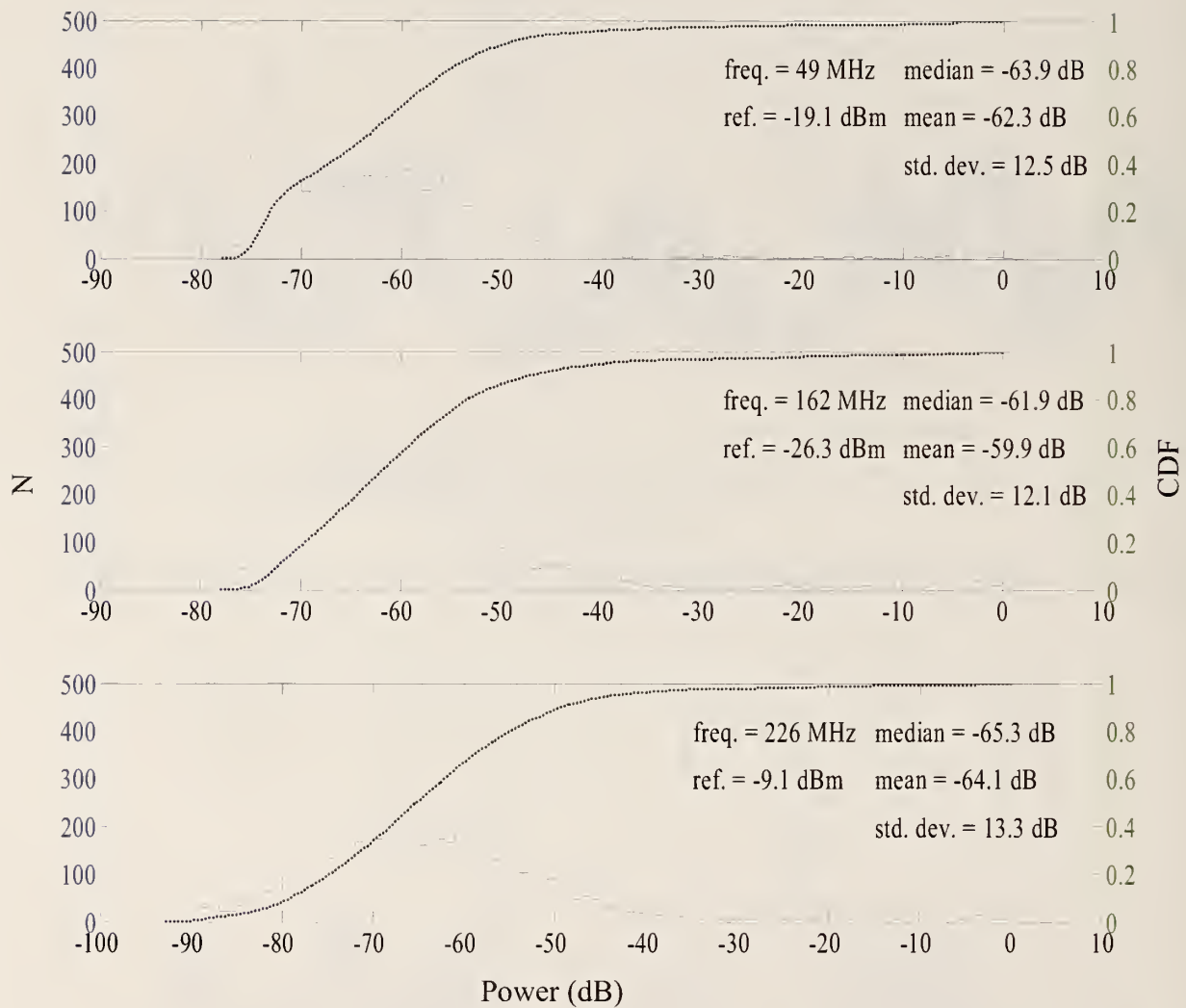


Figure 176. Washington, DC convention center statistics, histograms, and empirical CDF for walk-through data with the receiver at site 1; 49.60, 162.09, and 226.40 MHz.

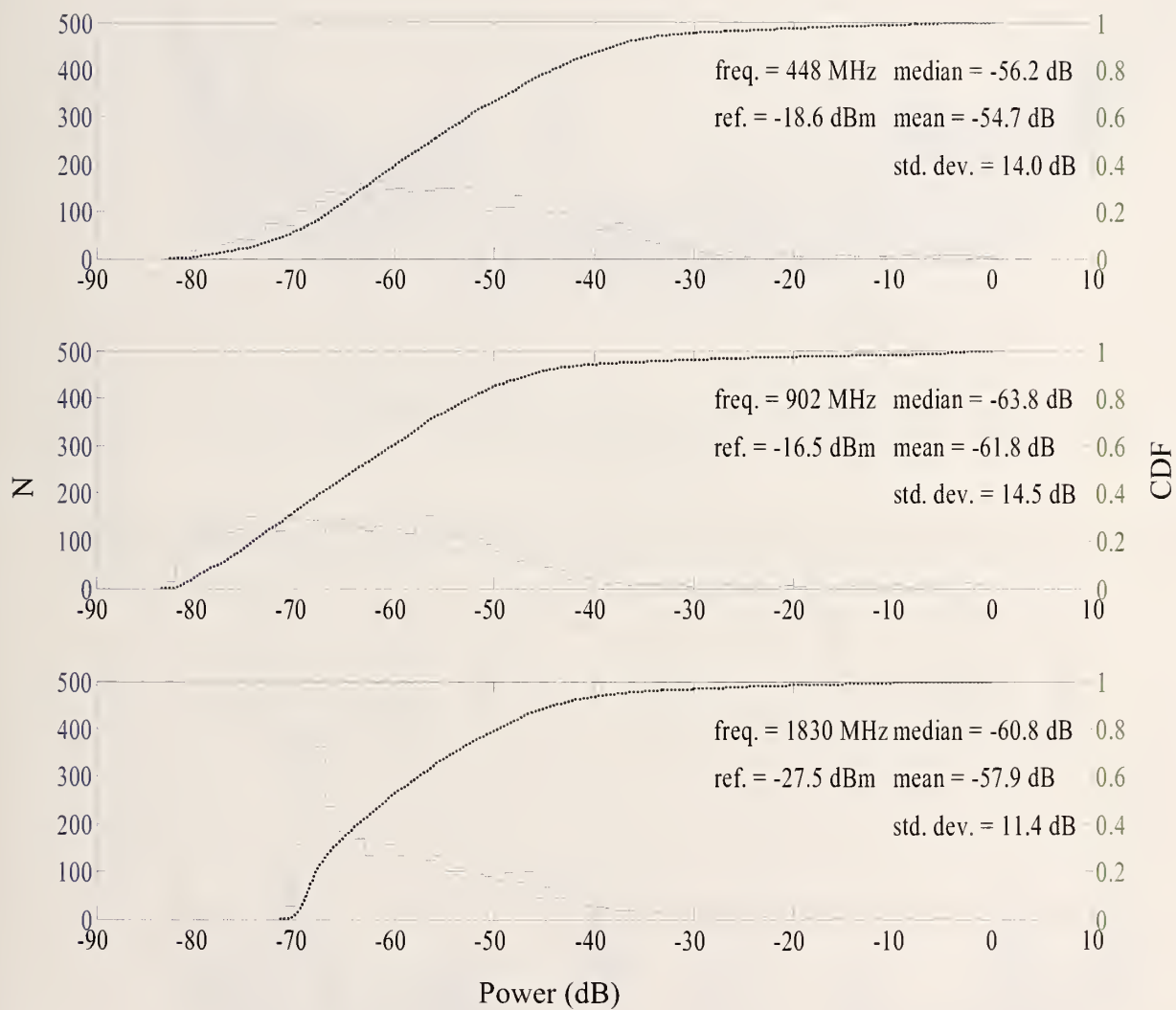


Figure 177. Washington, DC convention center statistics, histograms, and empirical CDF for walk-through data with the receiver at site 1; 448.30, 902.45, and 1830.00 MHz.



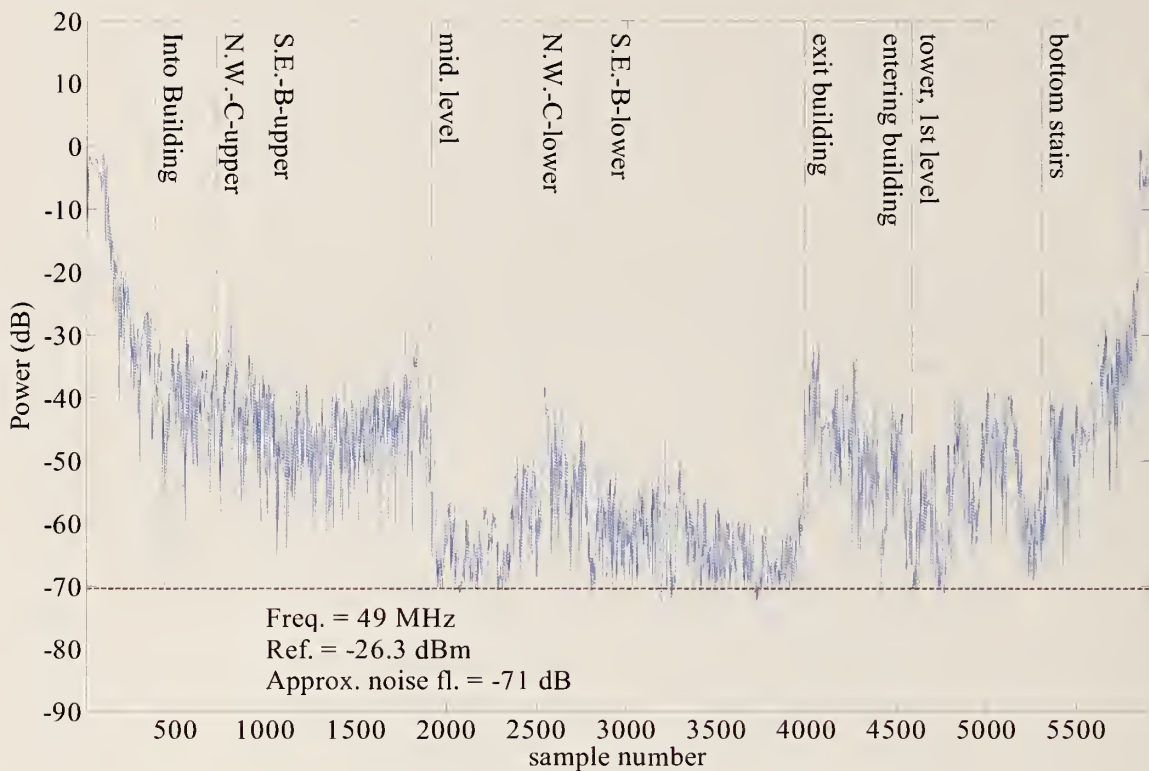


Figure 178. Washington, DC convention center walk-through at 49.60 MHz; receiver at site 2.

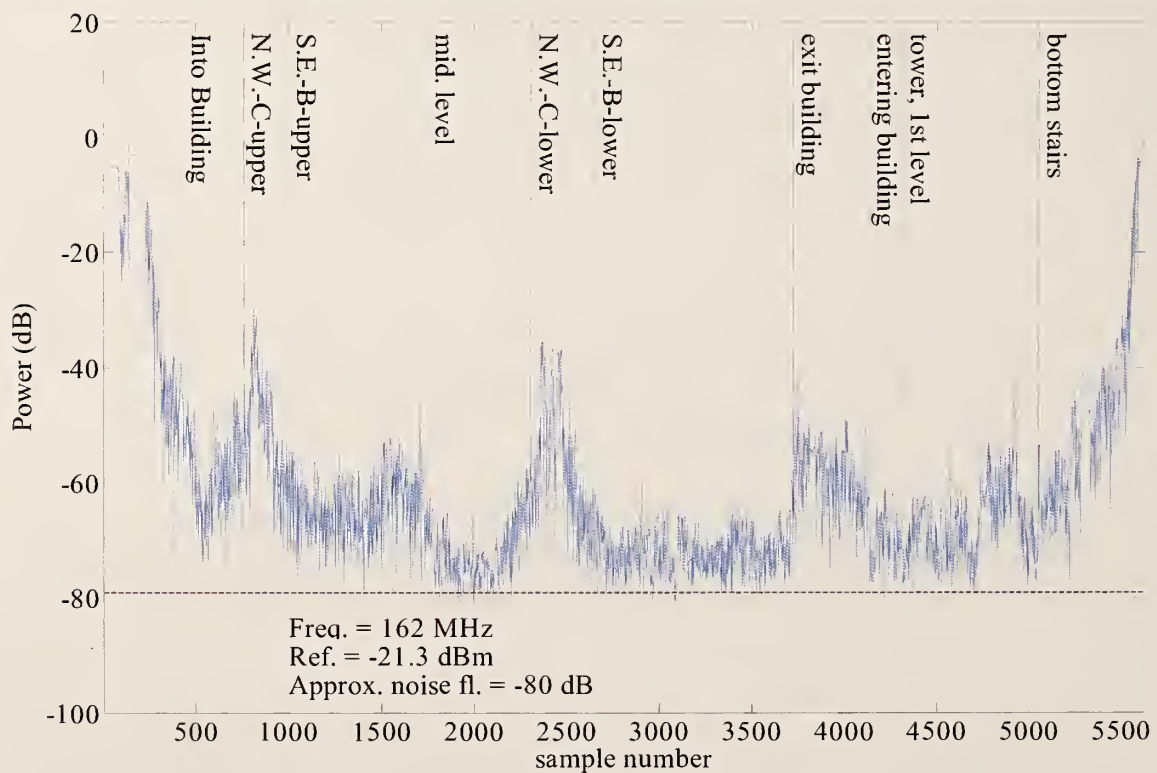


Figure 179. Washington, DC convention center walk-through at 162.09 MHz; receiver at site 2.

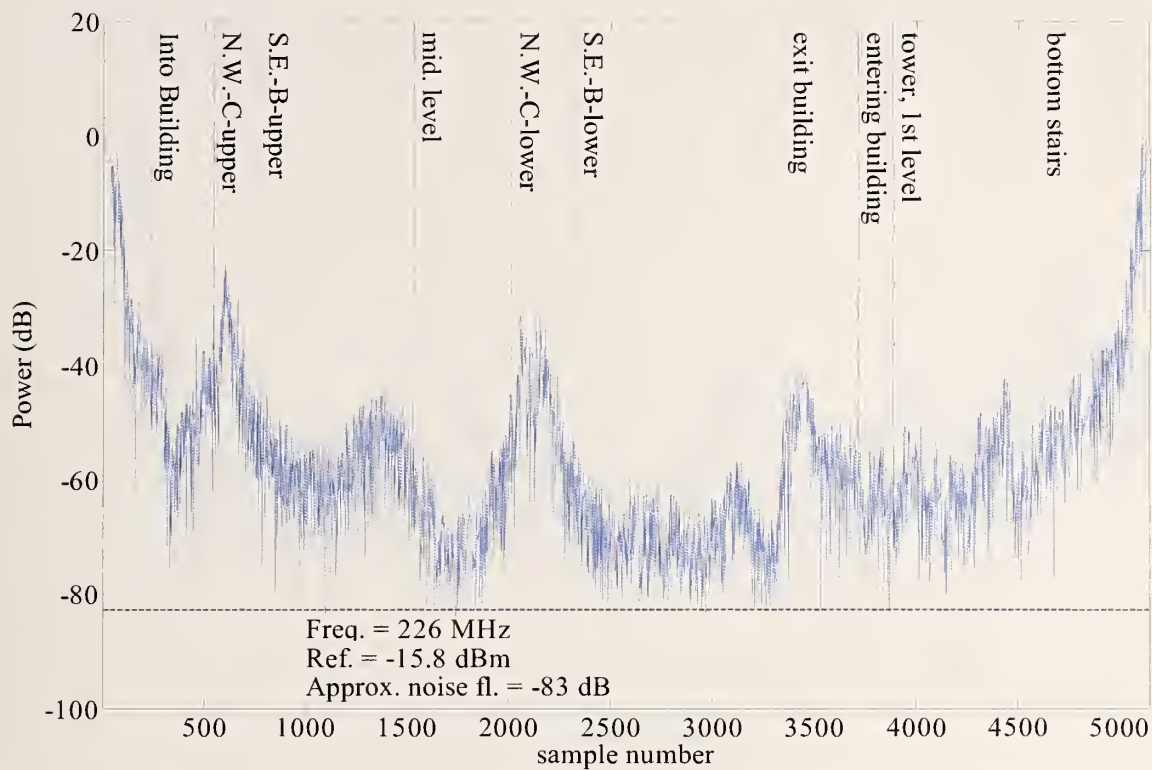


Figure 180. Washington, DC convention center walk-through at 226.40 MHz; receiver at site 2.

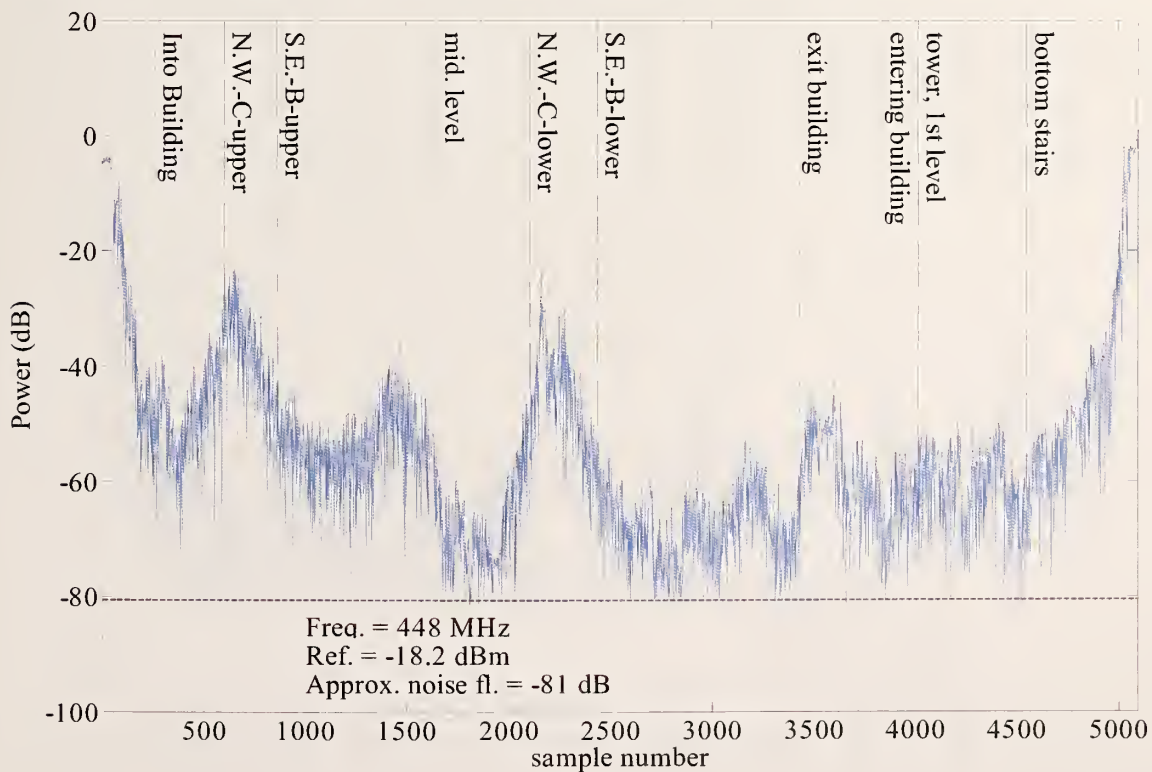


Figure 181. Washington, DC convention center walk-through at 448.30 MHz; receiver at site 2.

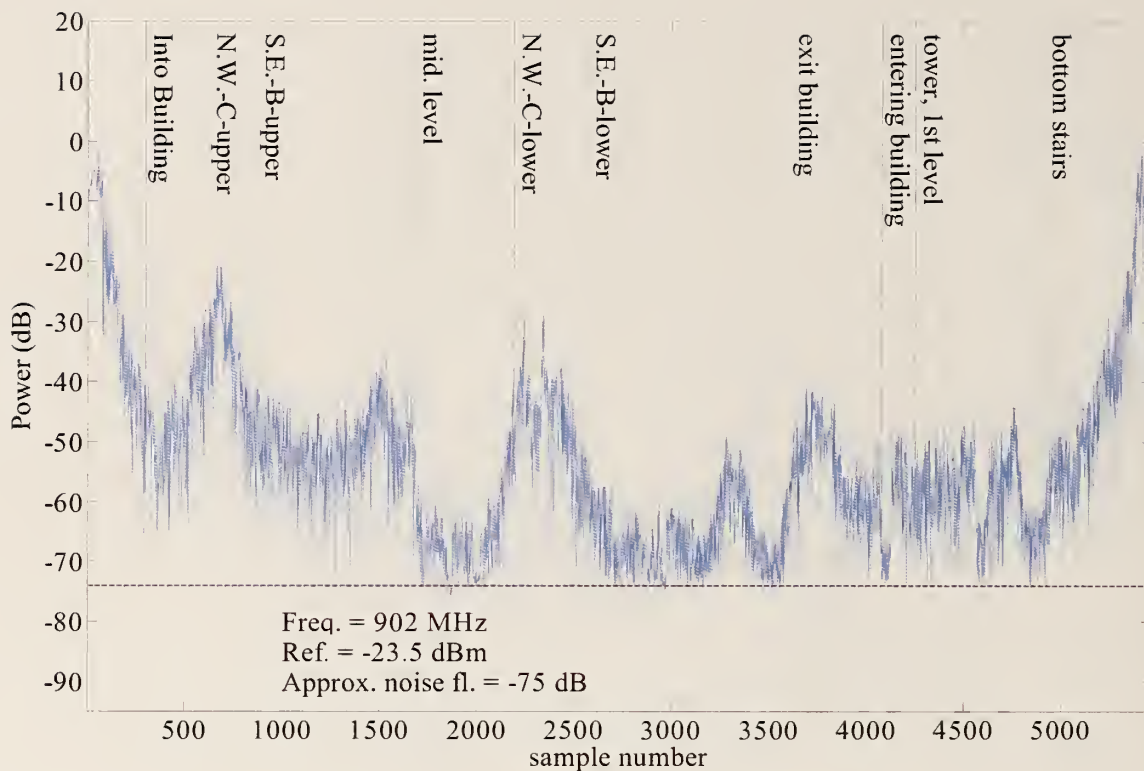


Figure 182. Washington, DC convention center walk-through at 902.45 MHz; receiver at site 2.

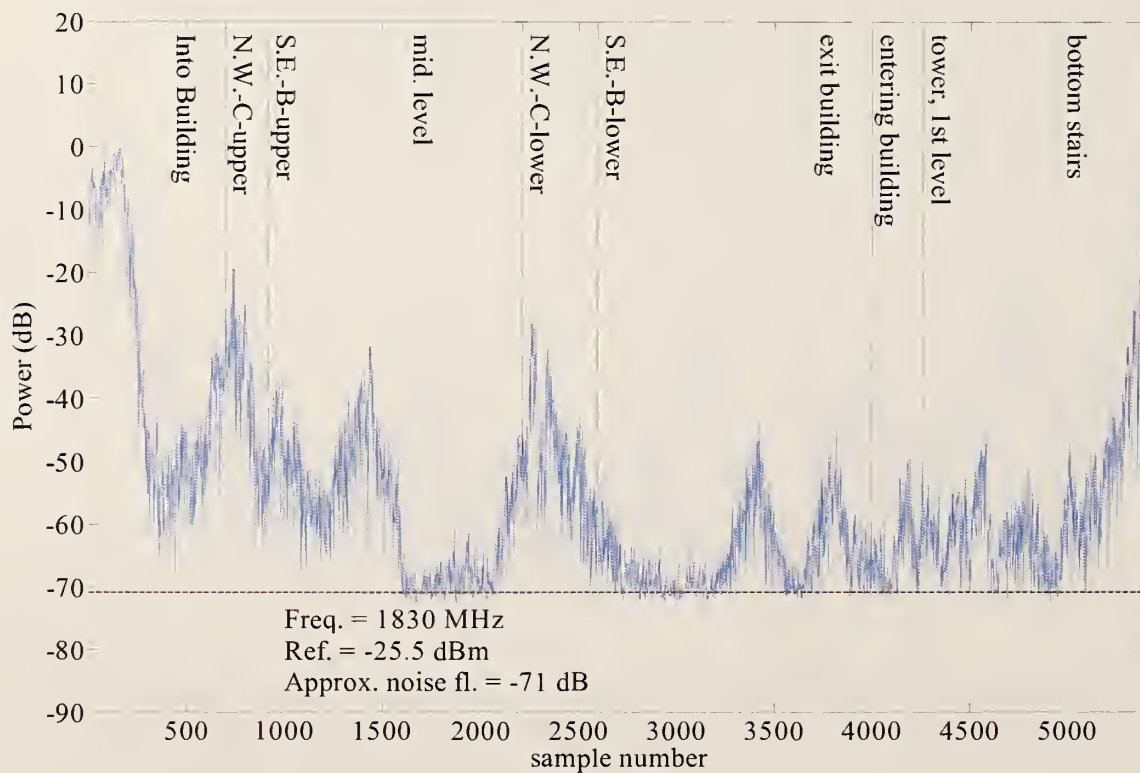


Figure 183. Washington, DC convention center walk-through at 1830.00 MHz; receiver at site 2.

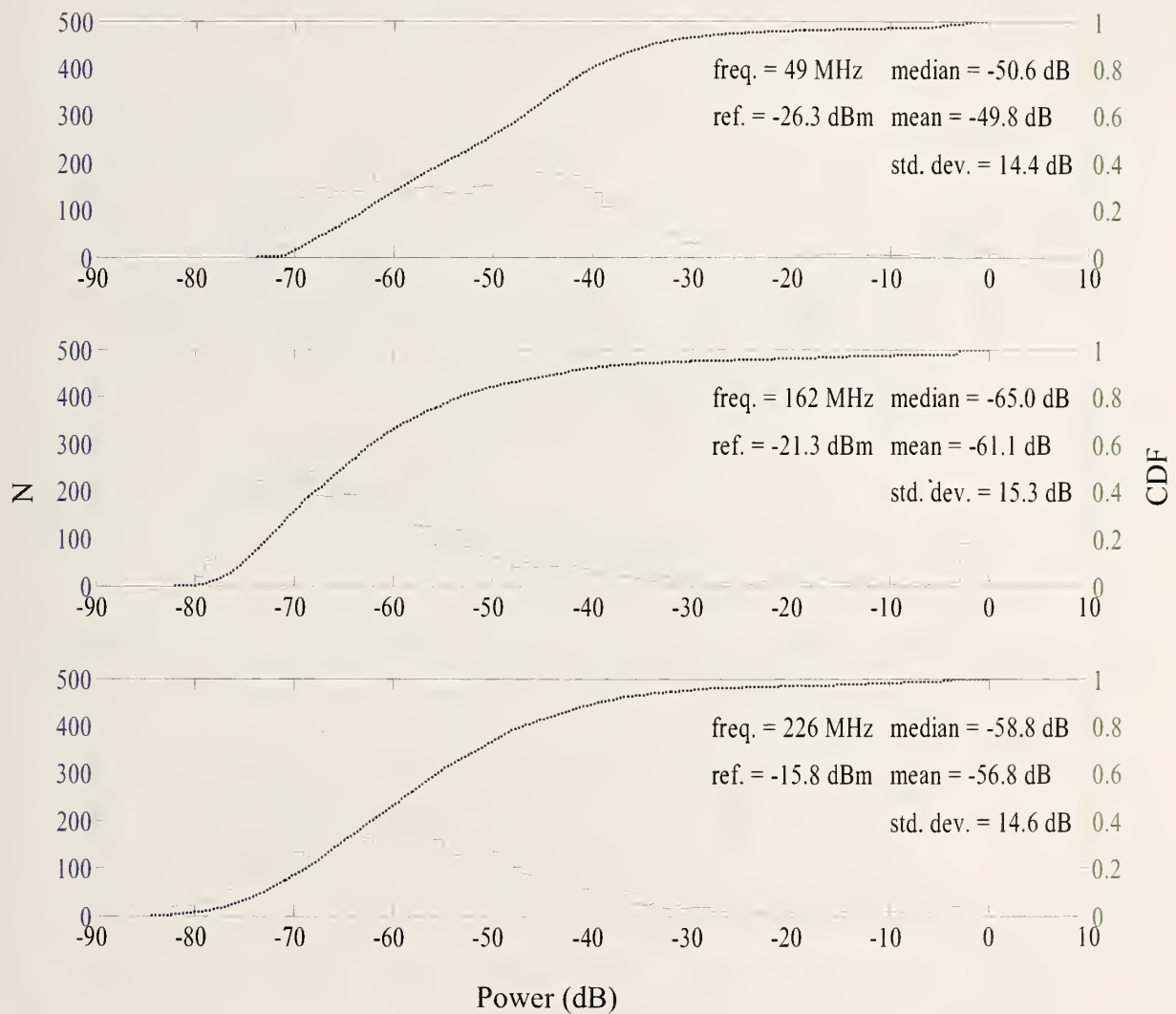


Figure 184. Washington, DC convention center statistics, histograms, and empirical CDF for walk-through data with the receiver at site 2; 49.60, 162.09, and 226.40 MHz.



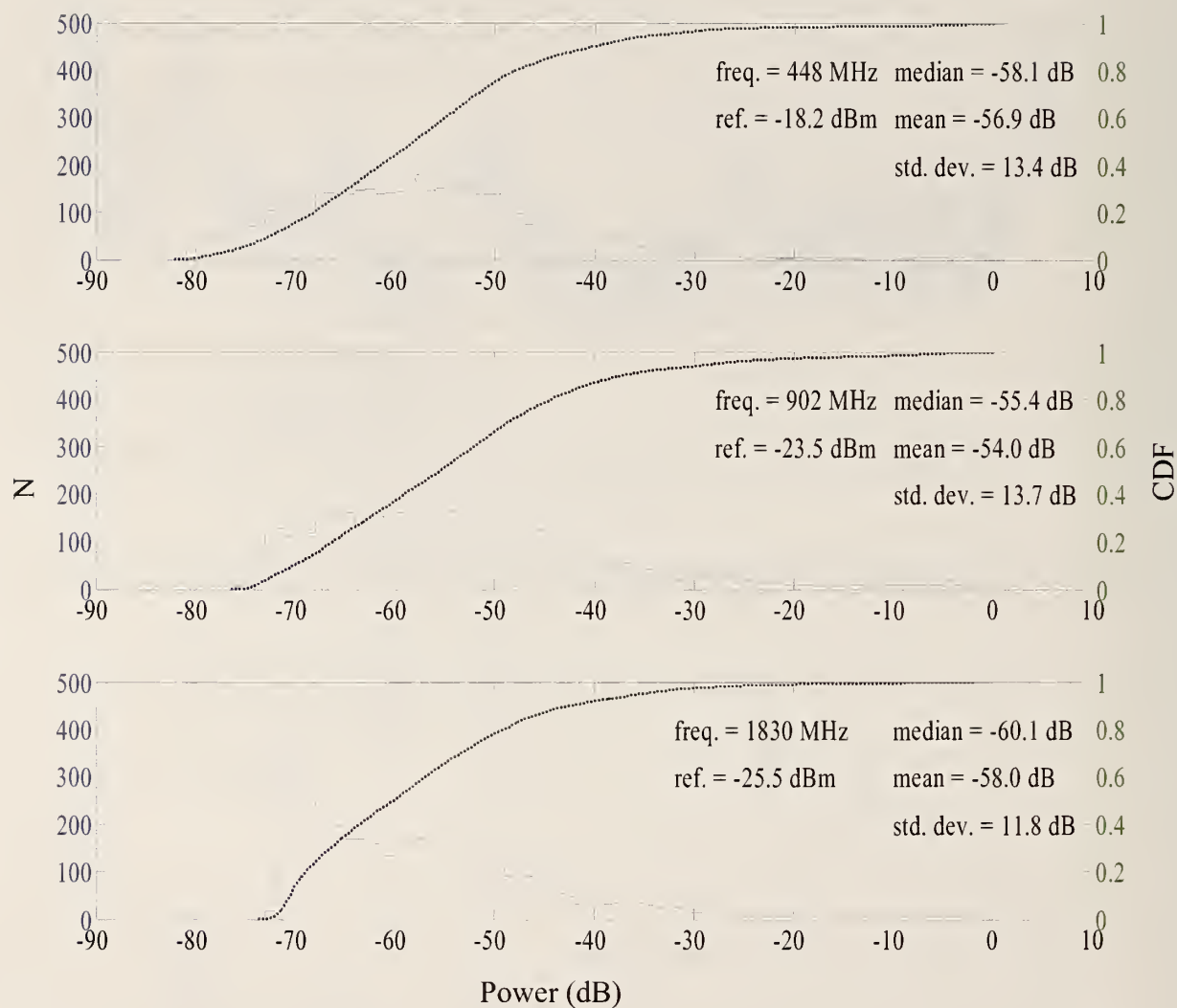


Figure 185. Washington, DC convention center statistics, histograms, and empirical CDF for walk-through data with the receiver at site 2; 448.30, 902.45, and 1830.00 MHz.

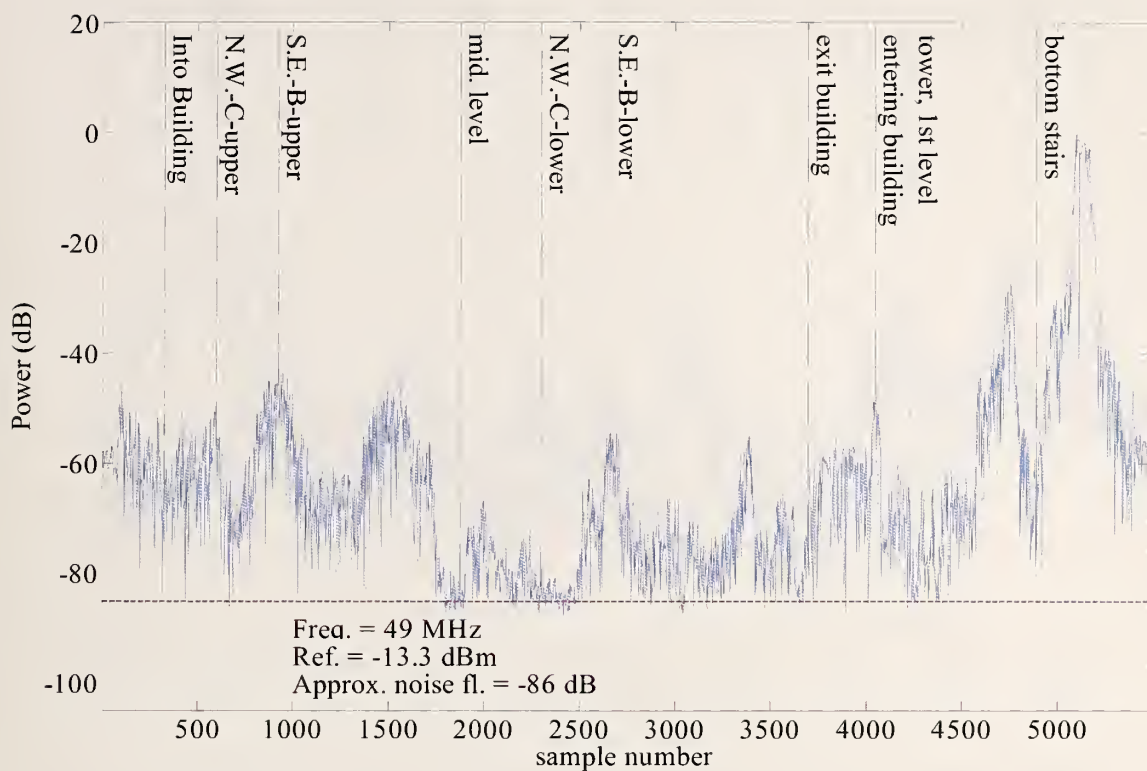


Figure 186. Washington, DC convention center walk-through at 49.60 MHz; receiver at site 3.

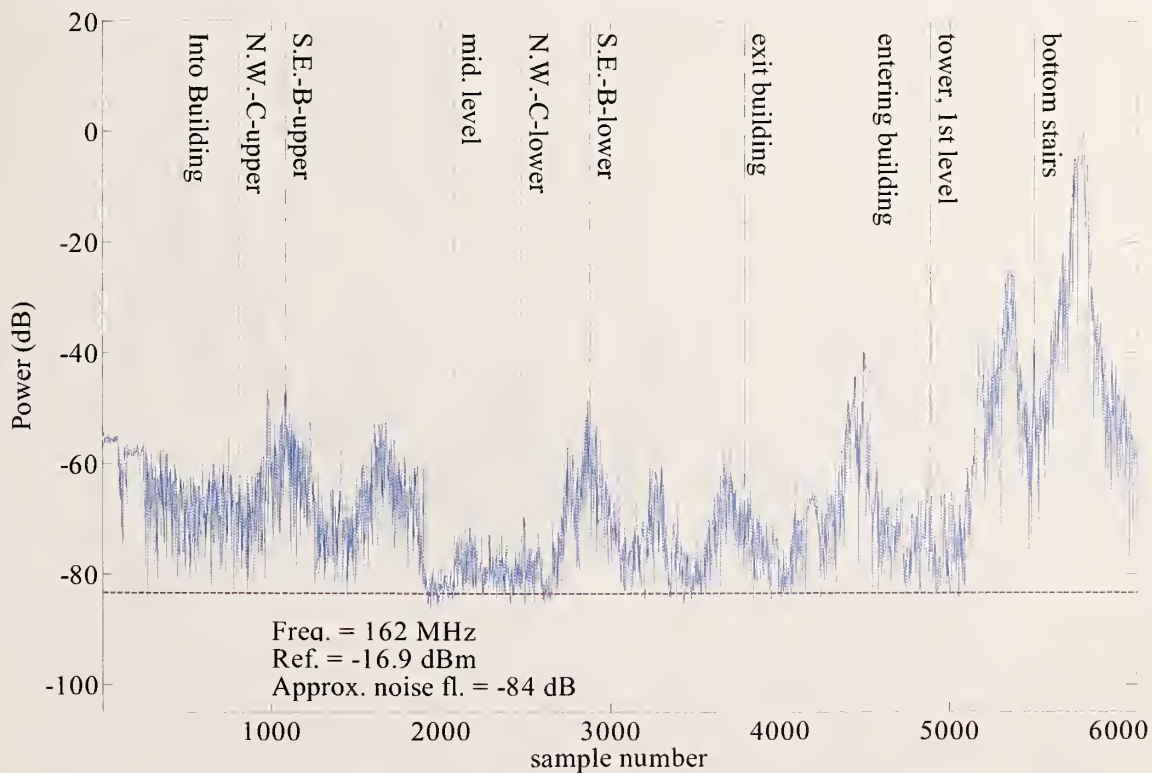


Figure 187. Washington, DC convention center walk-through at 162.09 MHz; receiver at site 3.

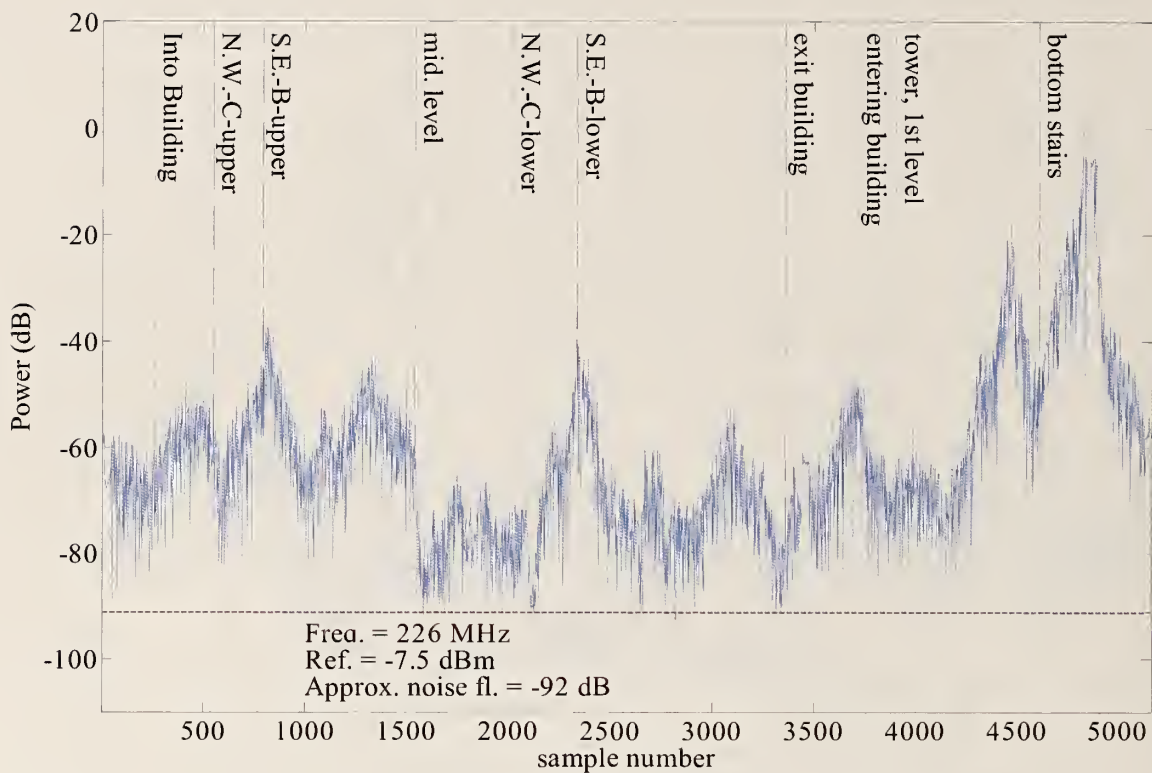


Figure 188. Washington, DC convention center walk-through at 226.40 MHz; receiver at site 3.

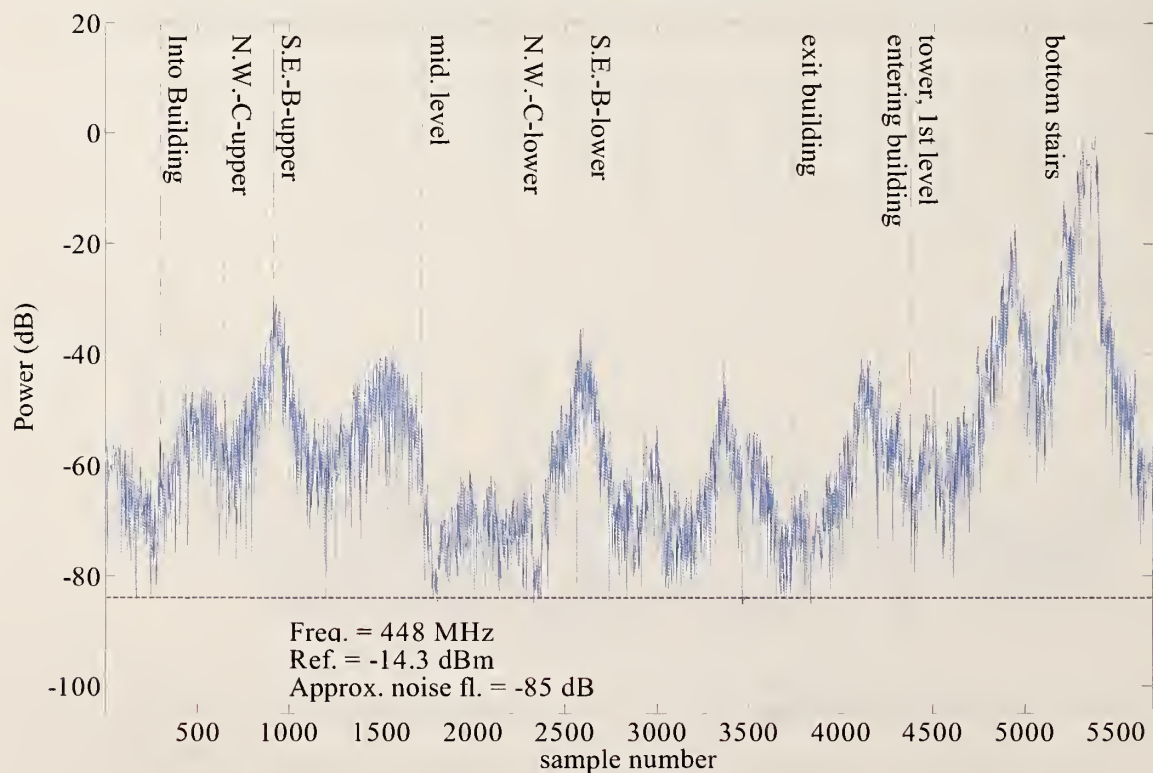


Figure 189. Washington, DC convention center walk-through at 448.30 MHz; receiver at site 3.

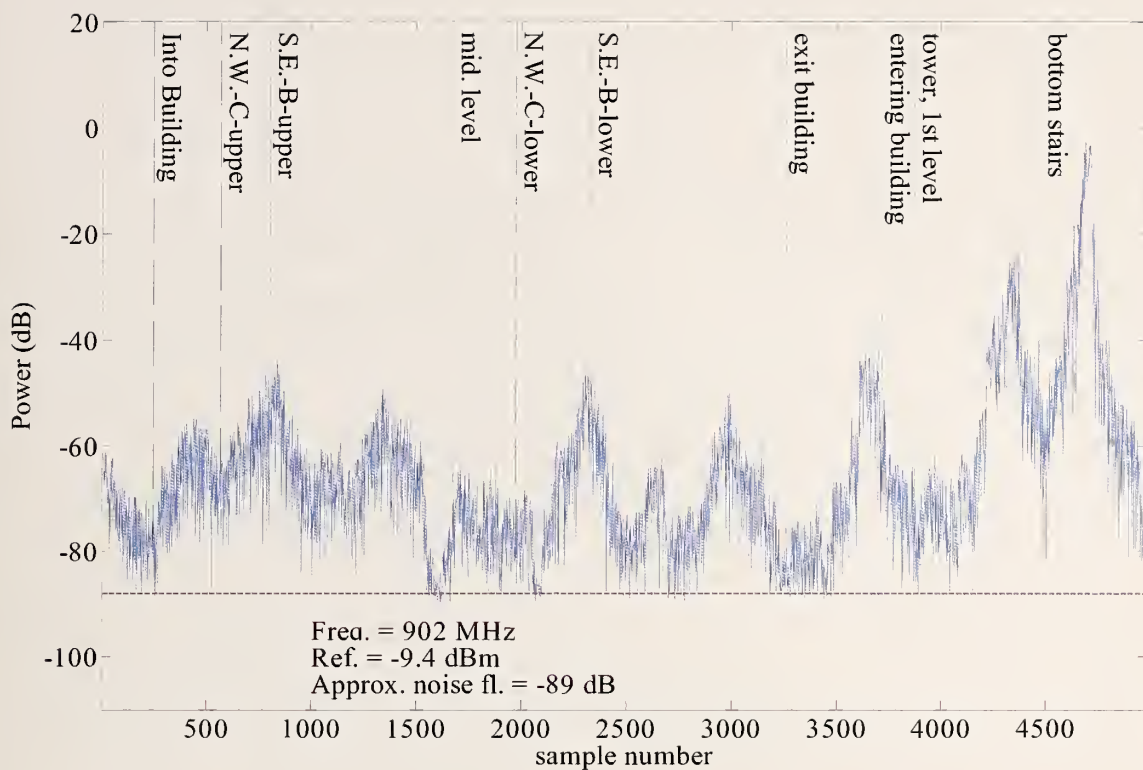


Figure 190. Washington, DC convention center walk-through at 902.45 MHz; receiver at site 3.

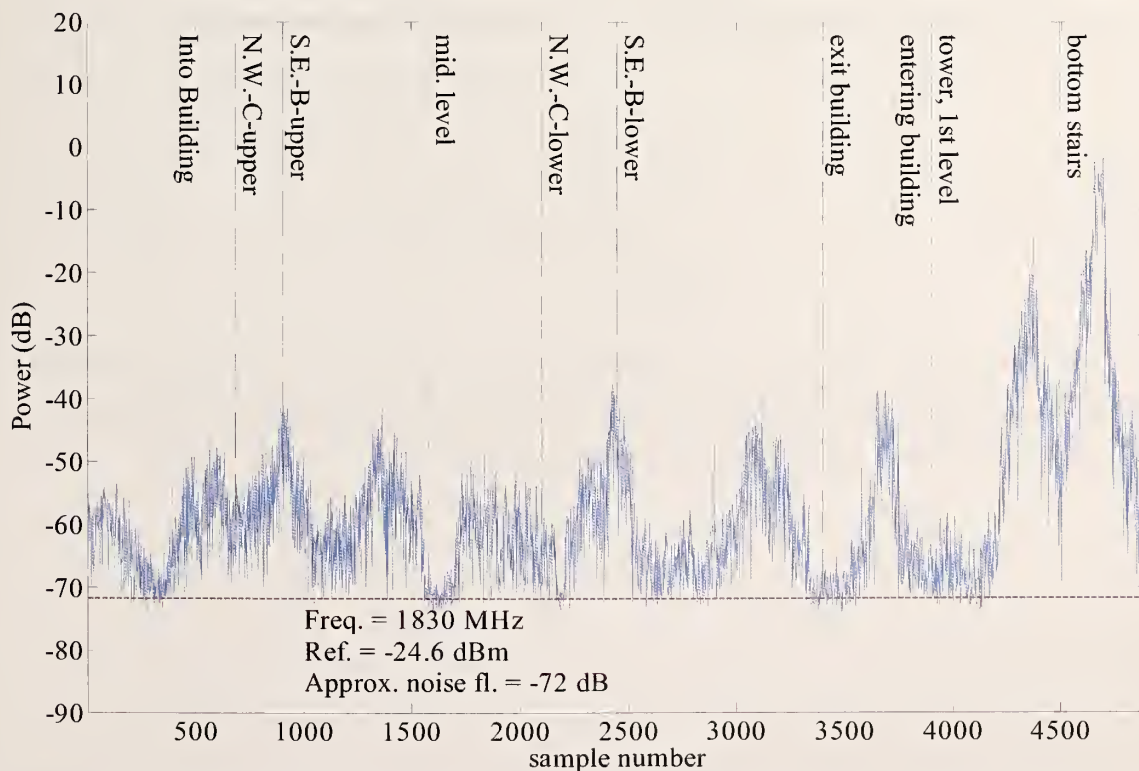


Figure 191. Washington, DC convention center walk-through at 1830.00 MHz; receiver at site 3.



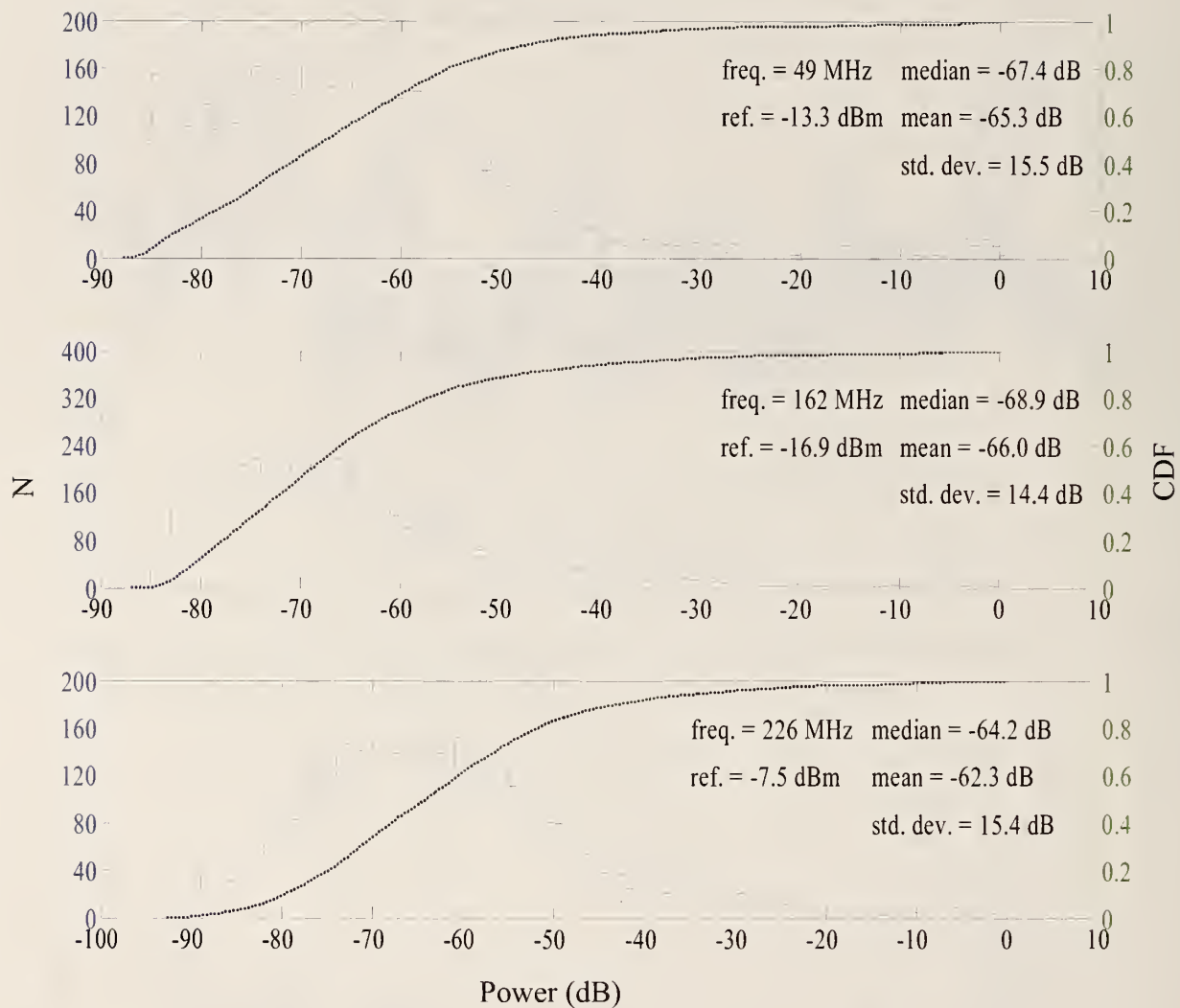


Figure 192. Washington, DC convention center statistics, histograms, and empirical CDF for walk-through data with the receiver at site 3; 49.60, 162.09, and 226.40 MHz.

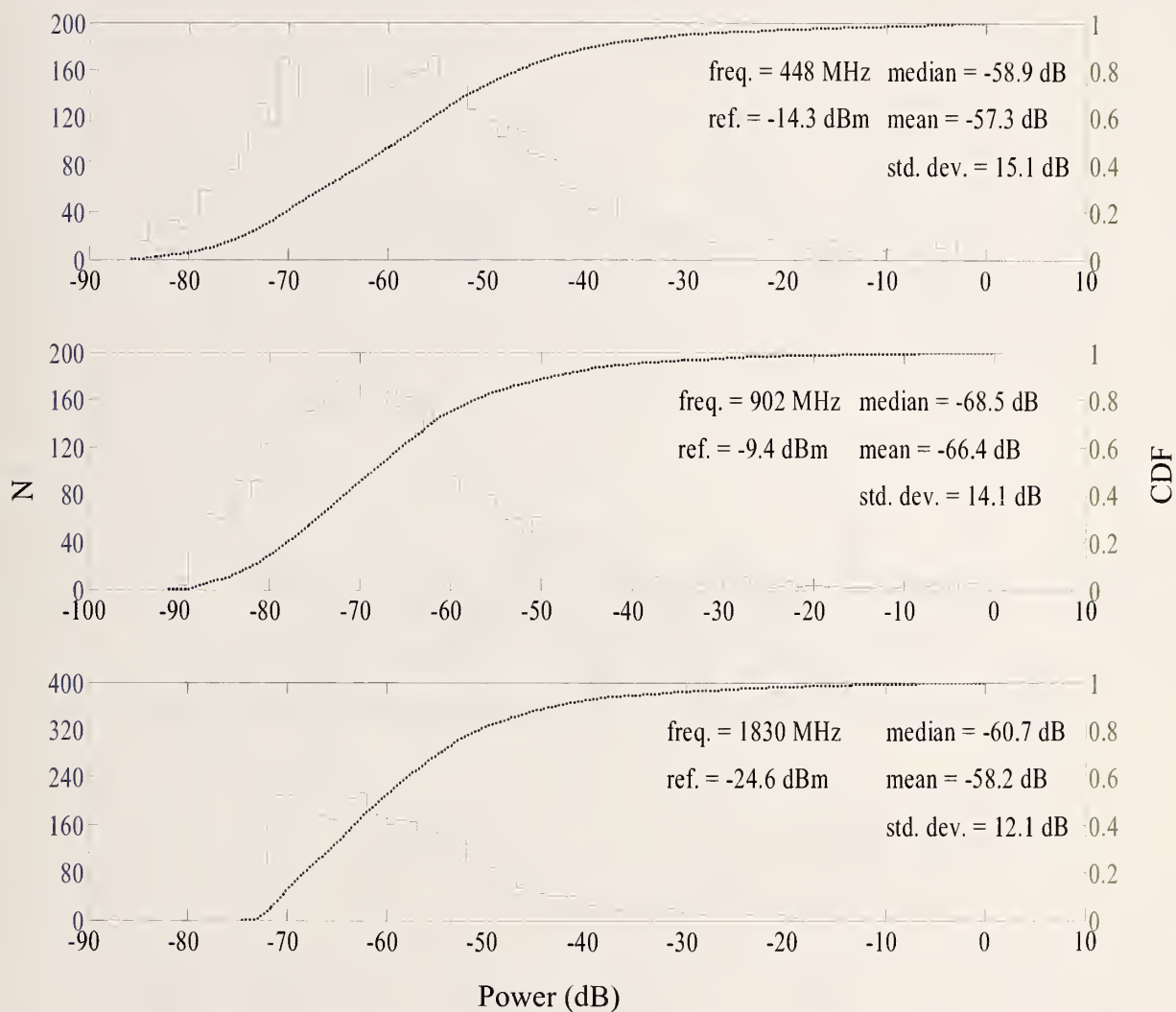


Figure 193. Washington, DC convention center statistics, histograms, and empirical CDF for walk-through data with the receiver at site 3; 448.30, 902.45, and 1830.00 MHz.

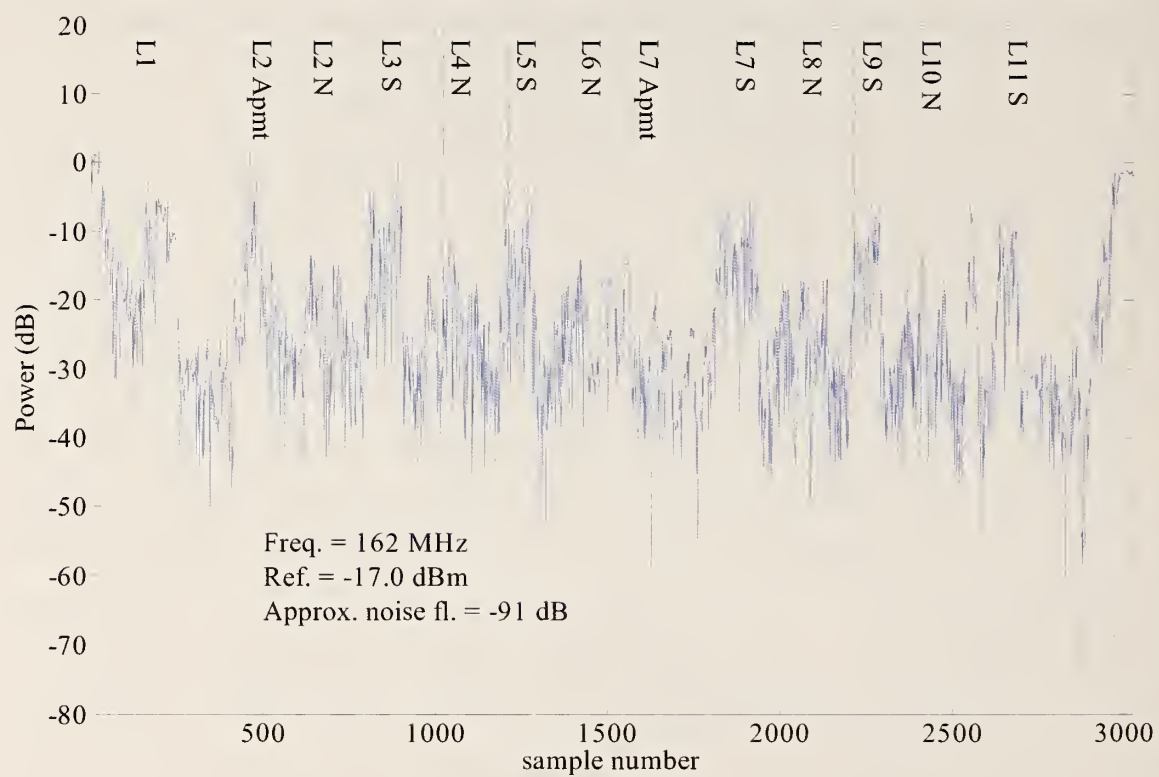


Figure 194. Boulder, CO apartment walk-through at 162.075 MHz; receiver at site 1.

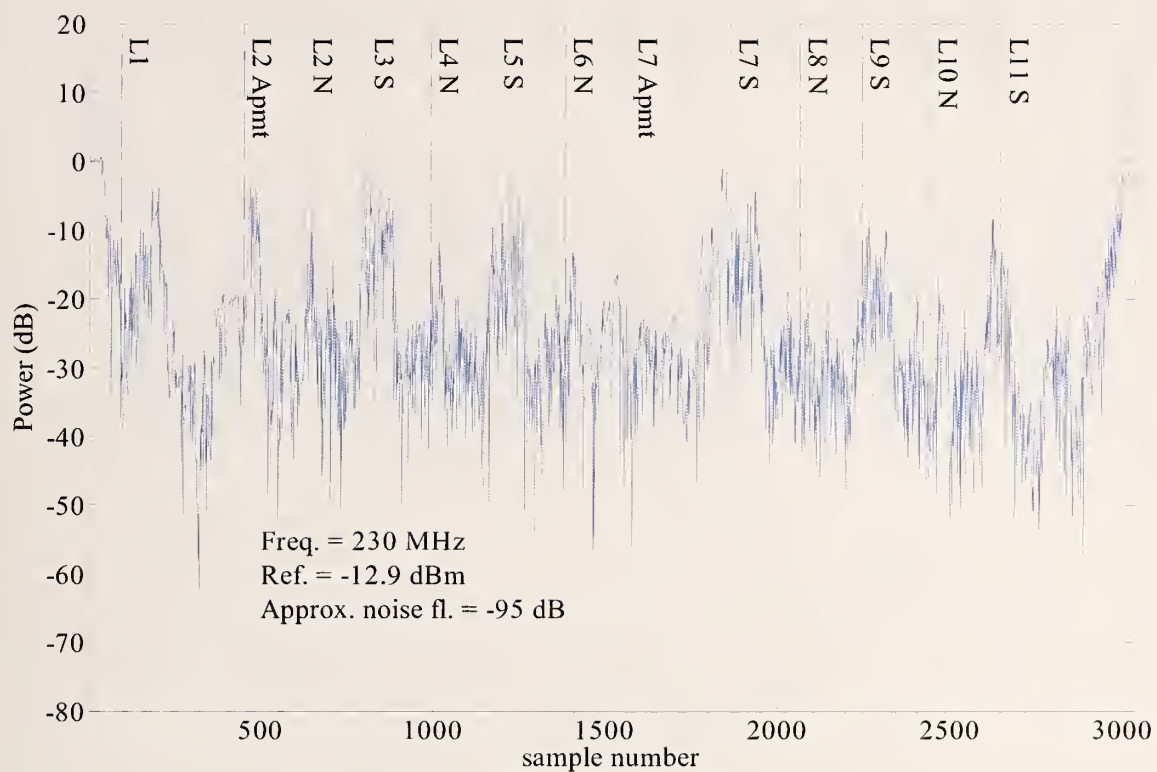


Figure 195. Boulder, CO apartment walk-through at 230.0 MHz; receiver at site 1.

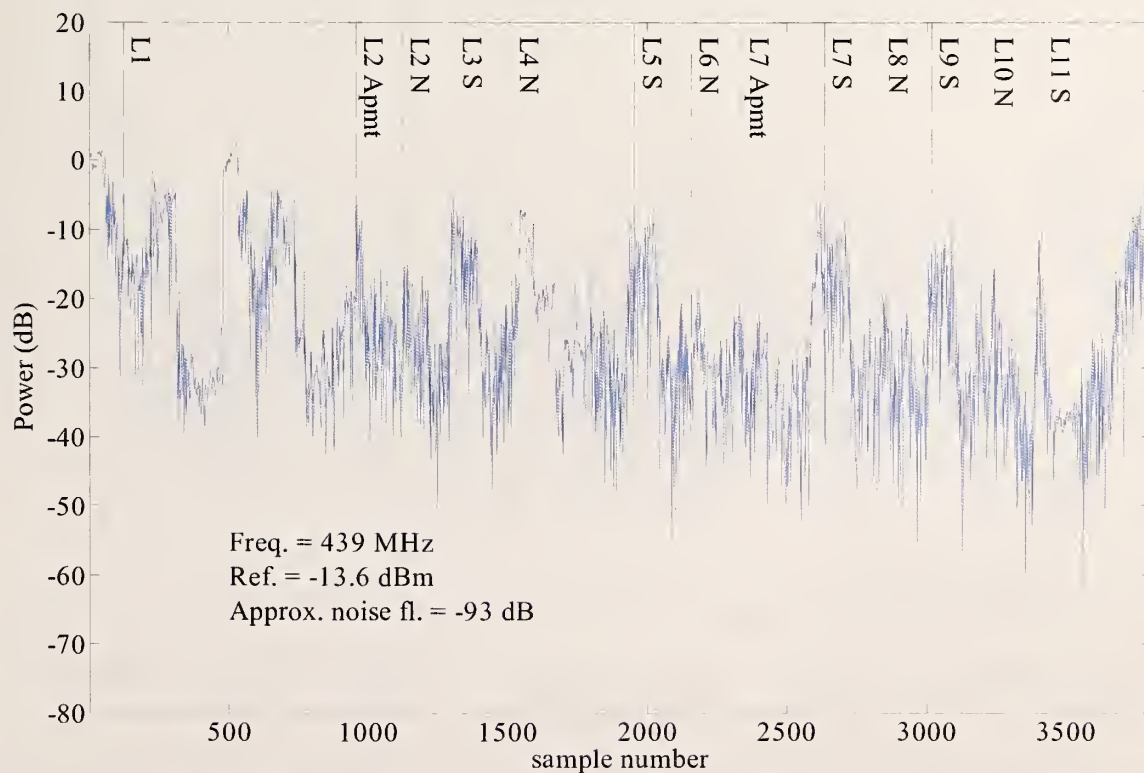


Figure 196. Boulder, CO apartment walk-through at 439.25 MHz; receiver at site 1.



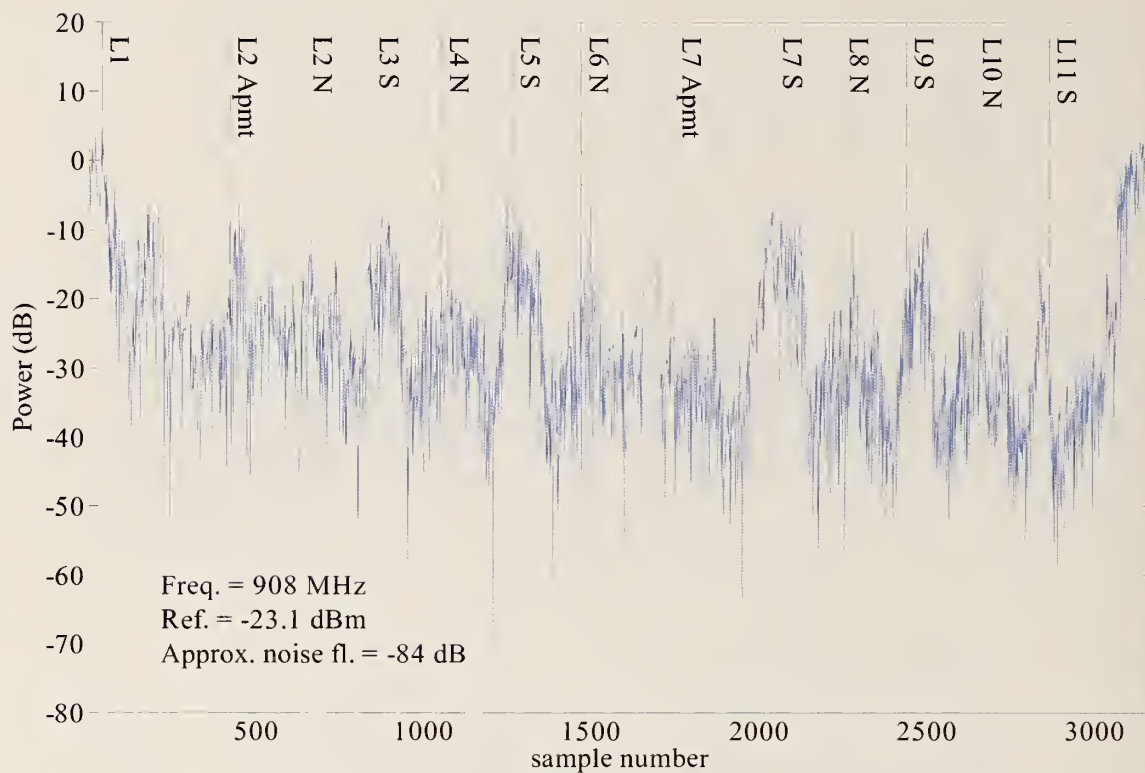


Figure 197. Boulder, CO apartment walk-through at 908.0 MHz; receiver at site 1.

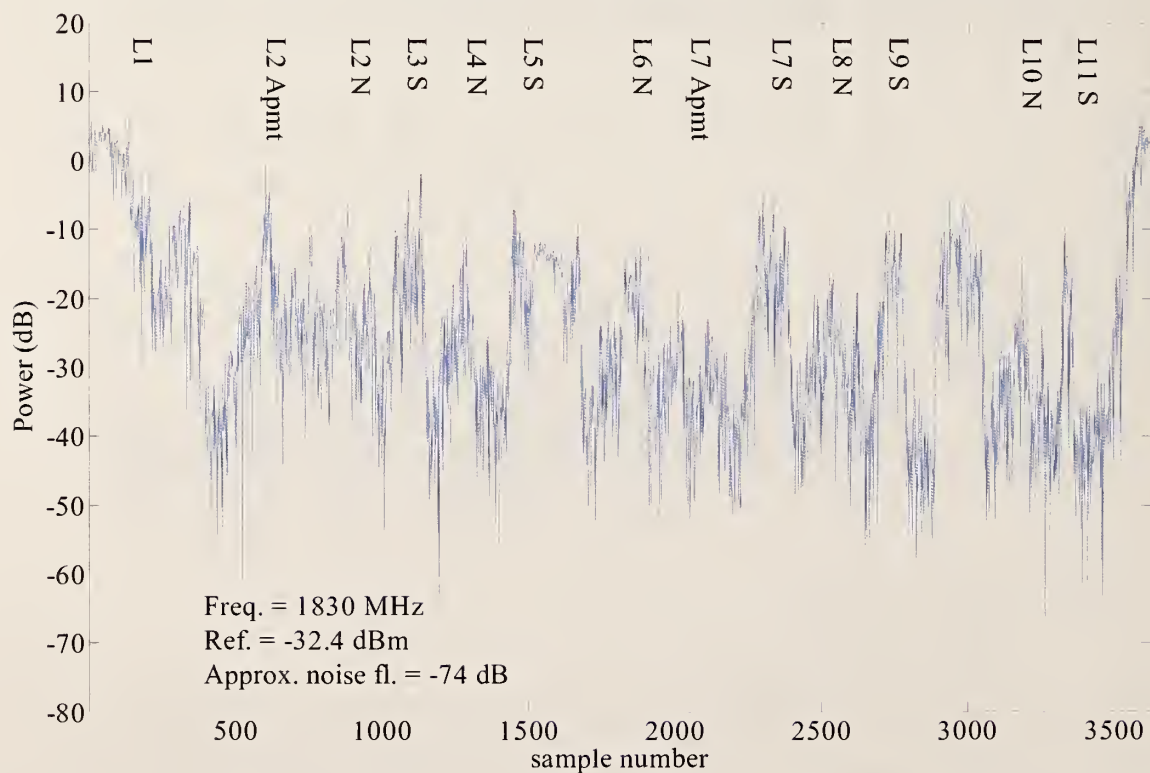


Figure 198. Boulder, CO apartment walk-through at 1830.0 MHz; receiver at site 1.

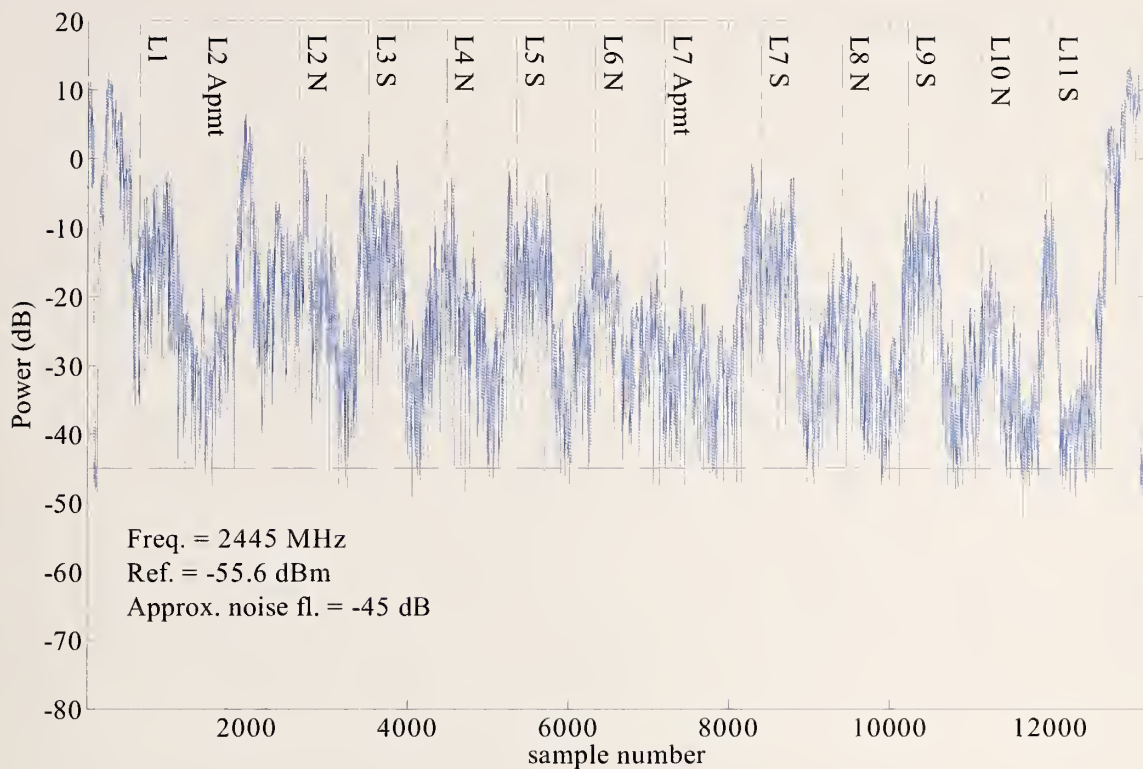


Figure 199. Boulder, CO apartment walk-through at 2445 MHz; receiver at site 1

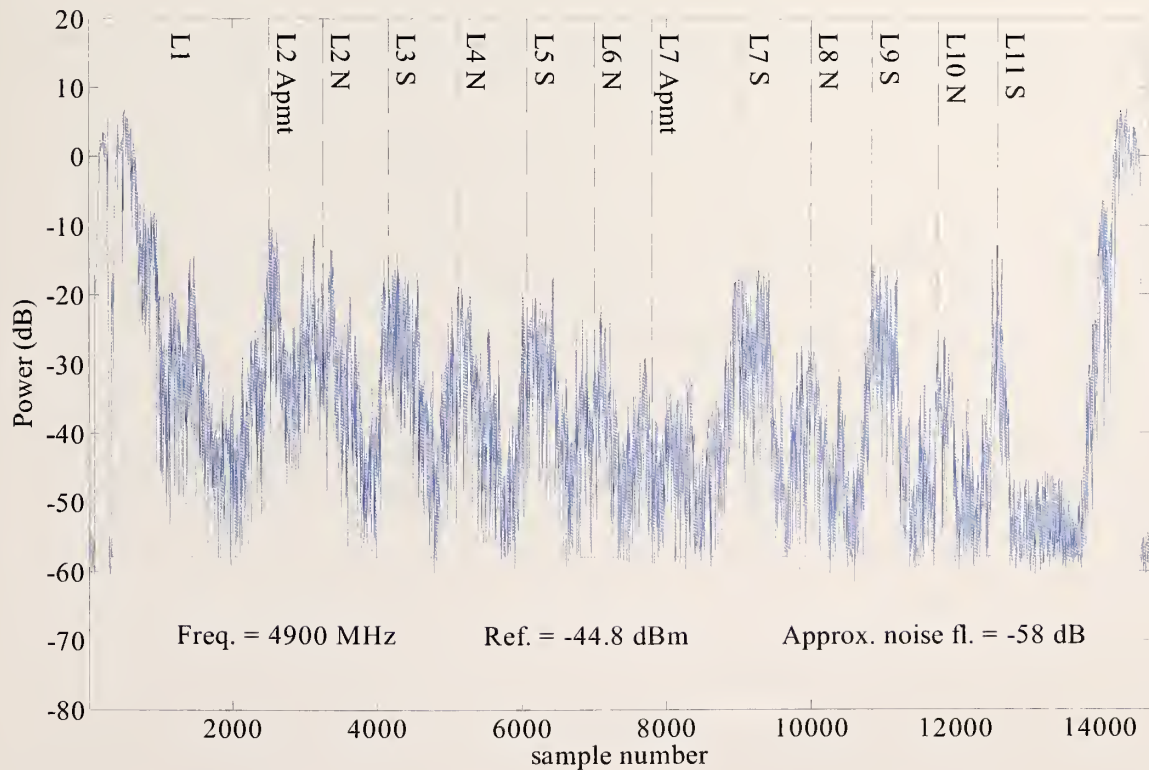


Figure 200. Boulder, CO apartment walk-through at 4900 MHz; receiver at site 1

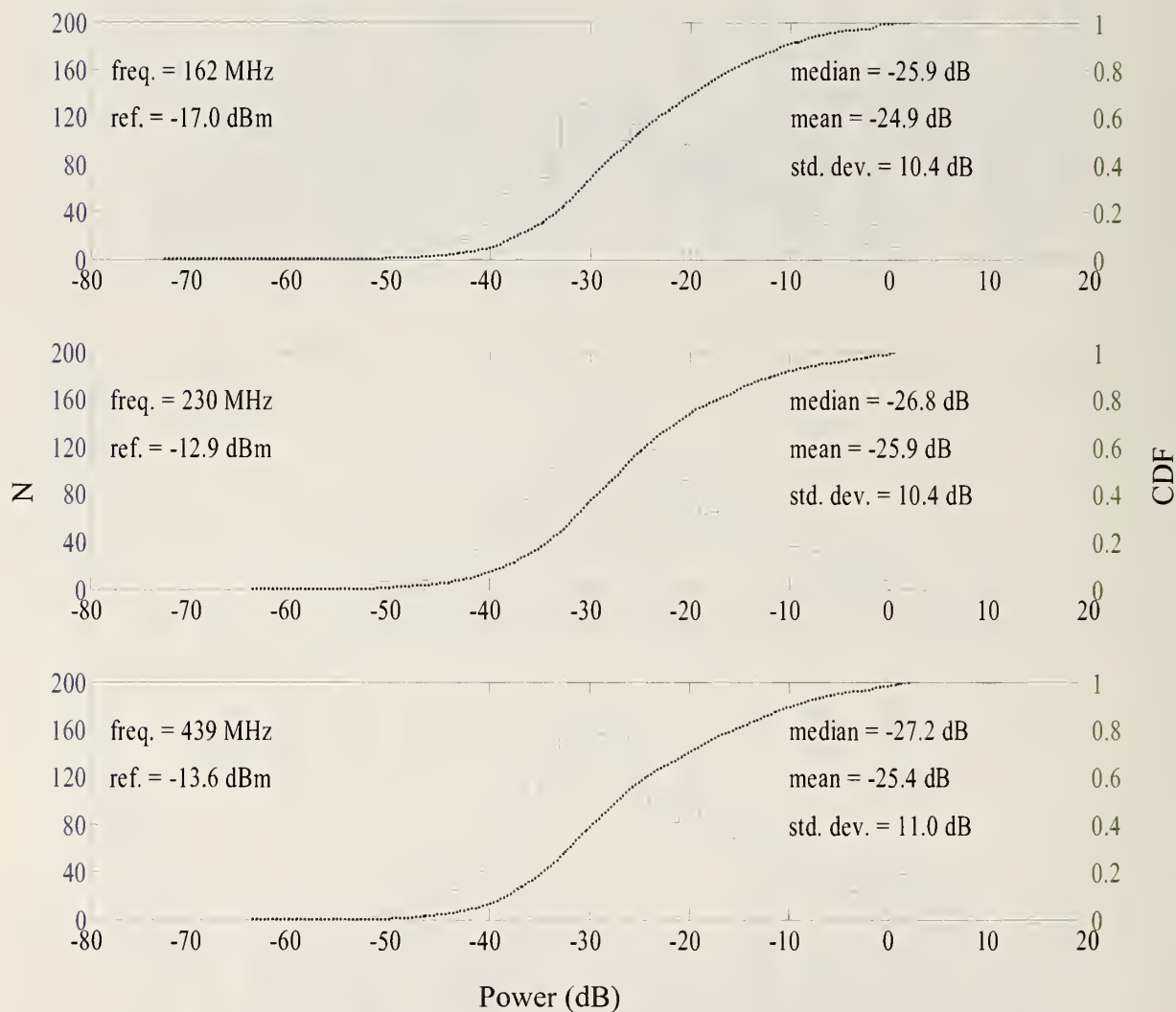


Figure 201. Boulder, CO apartment walk-through statistics, histograms, and empirical CDF for walk-through data with the receiver at site 1; 162.075, 230.0 and 439.25 MHz.

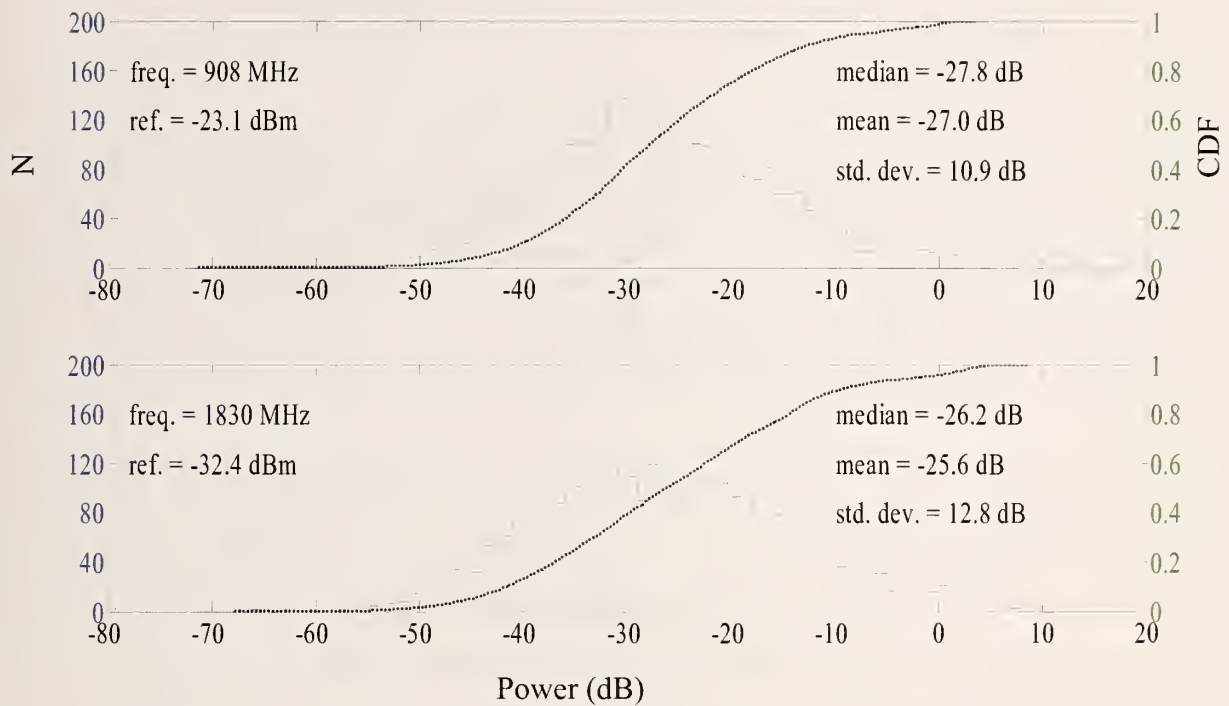


Figure 202. Boulder, CO apartment walk-through statistics, histograms, and empirical CDF for walk-through data with the receiver at site 1; 908.0 and 1830.0 MHz.



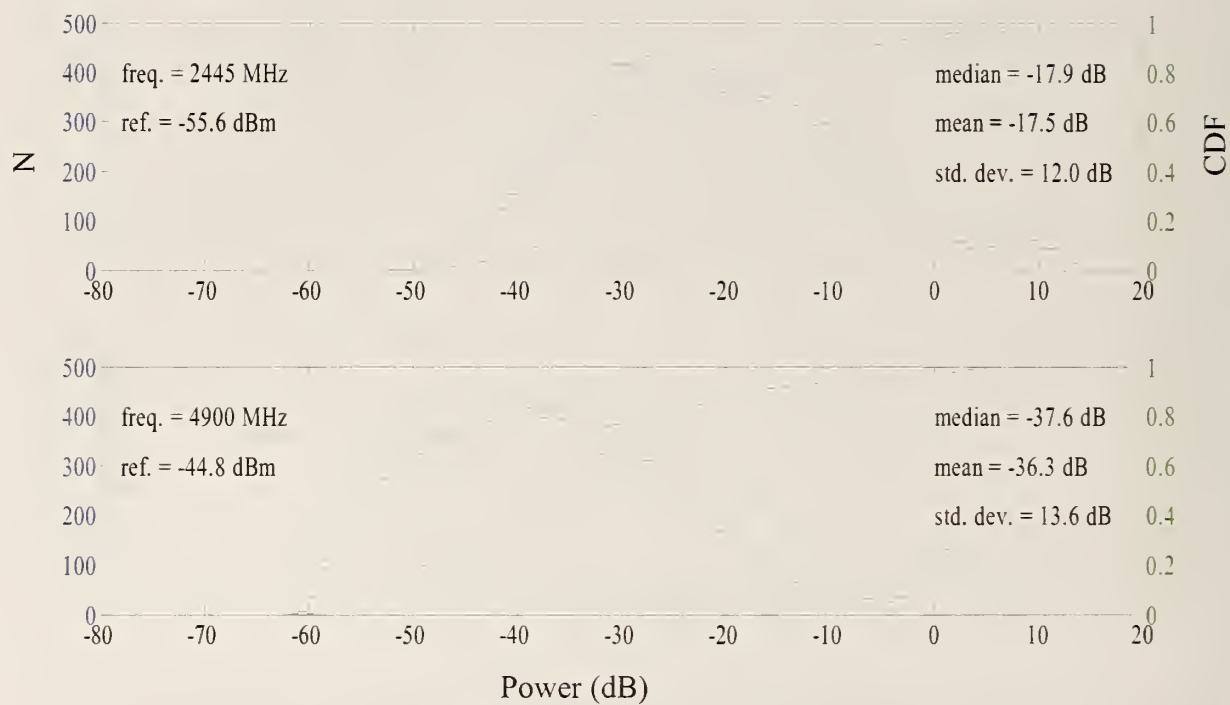


Figure 203. Boulder, CO apartment walk-through statistics, histograms, and empirical CDF for walk-through data with the receiver at site 1; 2445 and 4900 MHz.

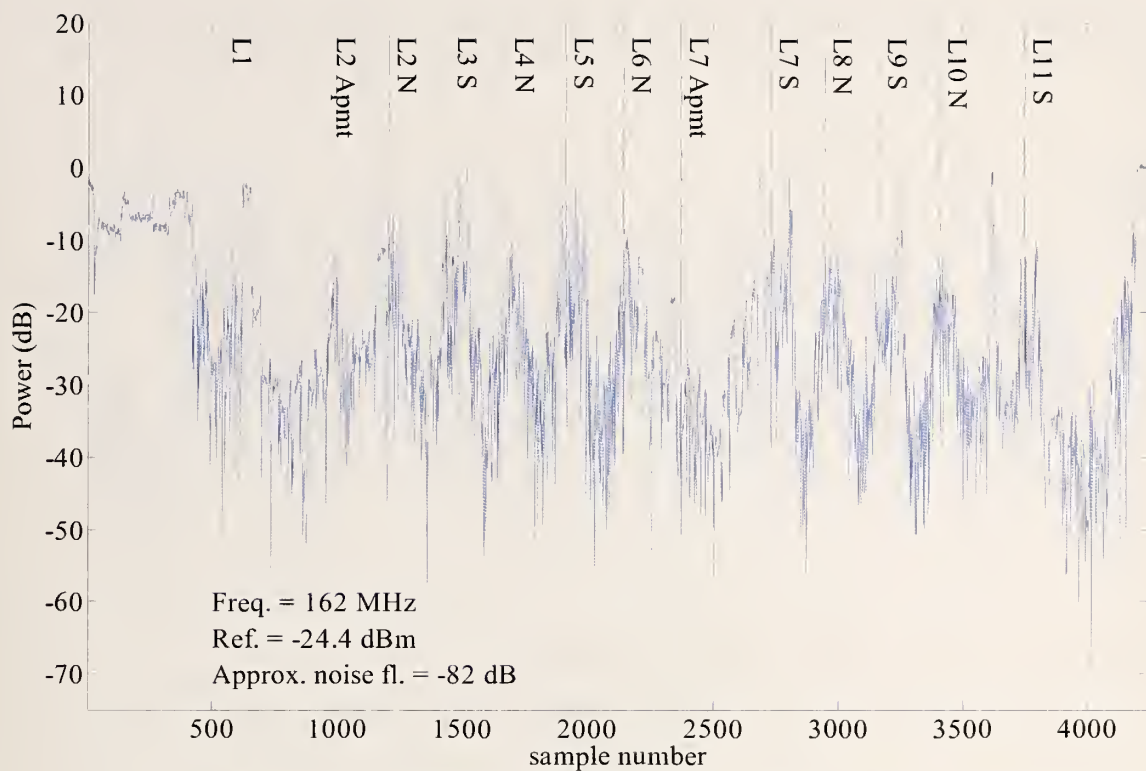


Figure 204. Boulder, CO apartment walk-through at 162.075 MHz; receiver at site 2.

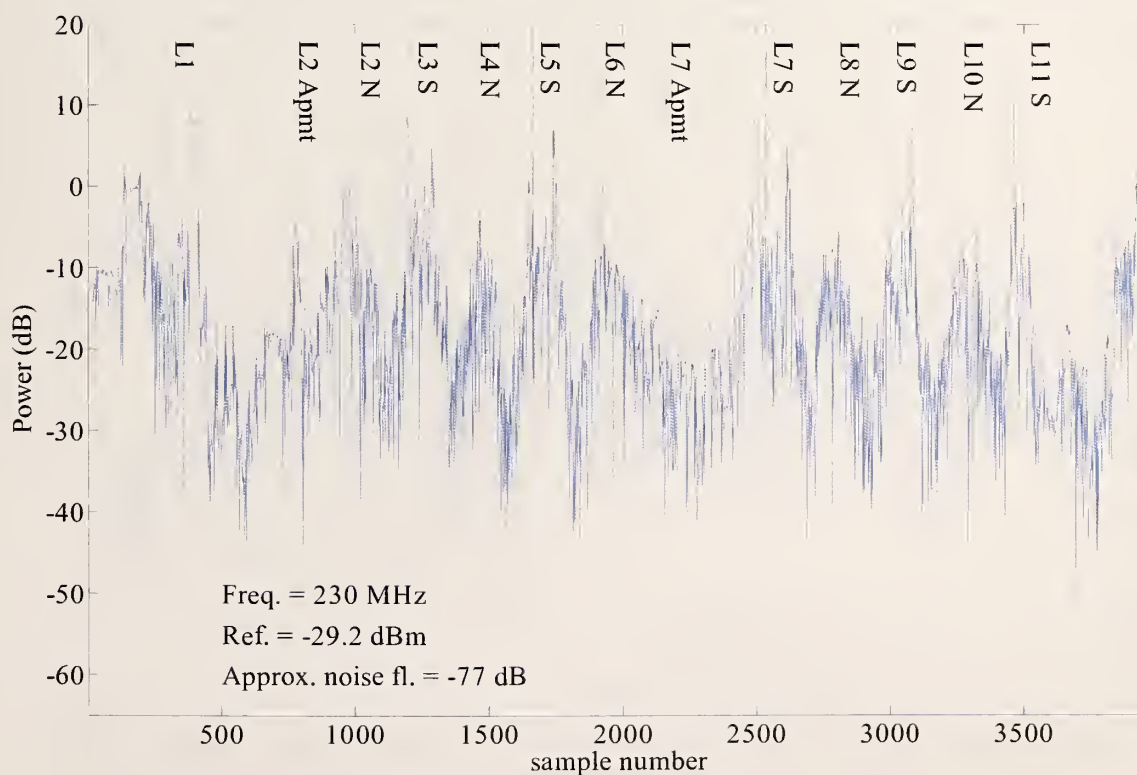


Figure 205. Boulder, CO apartment walk-through at 230.0 MHz; receiver at site 2.

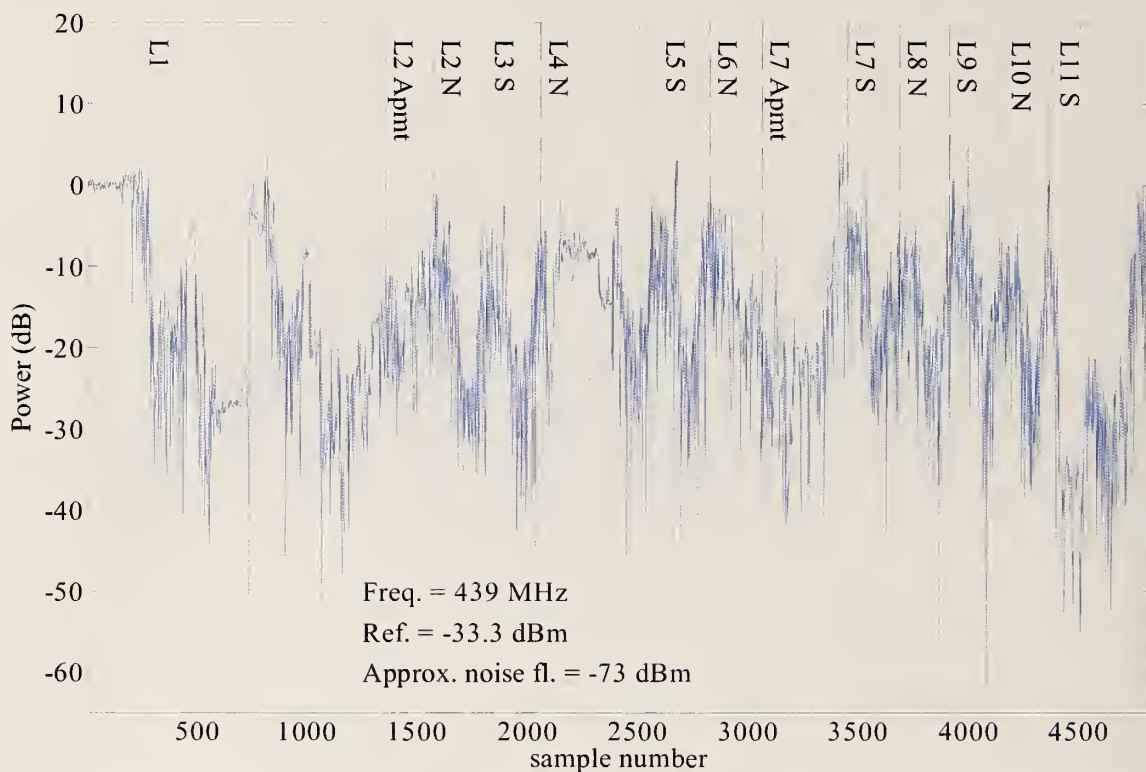


Figure 206. Boulder, CO apartment walk-through at 439.25 MHz; receiver at site 2.

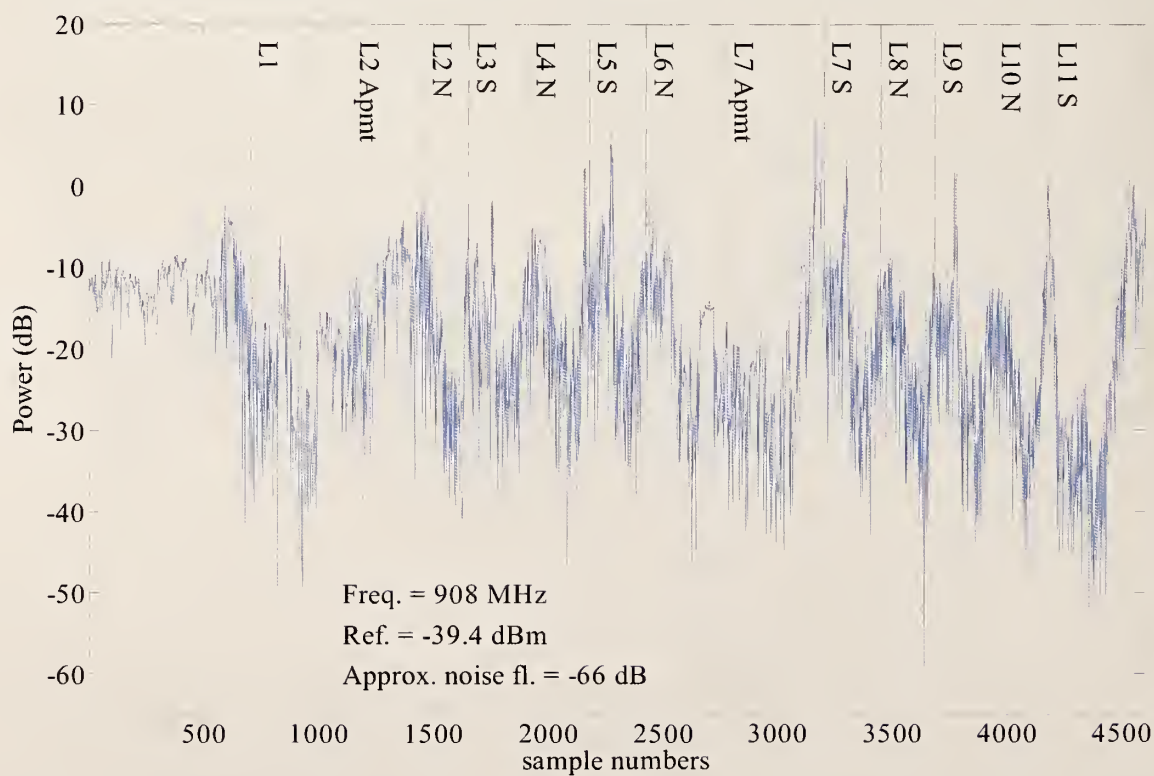


Figure 207. Boulder, CO apartment walk-through at 908.0 MHz; receiver at site 2.

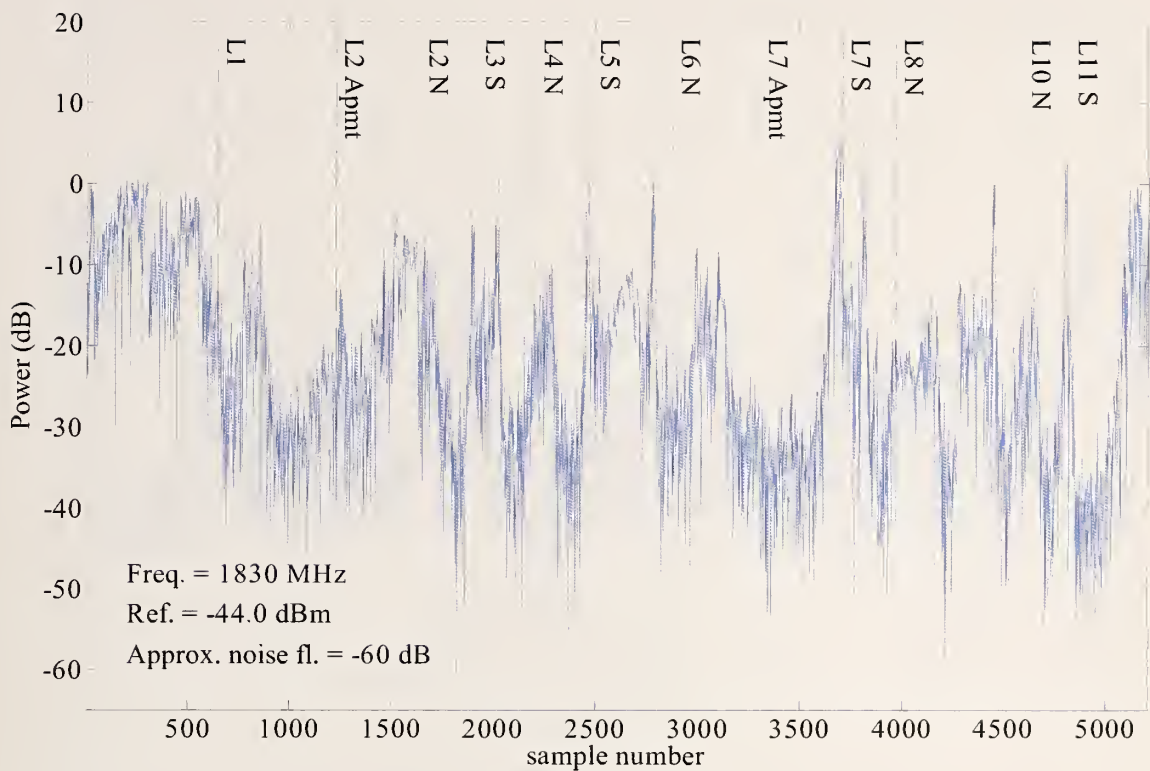


Figure 208. Boulder, CO apartment walk-through at 1830.0 MHz; receiver at site 2.

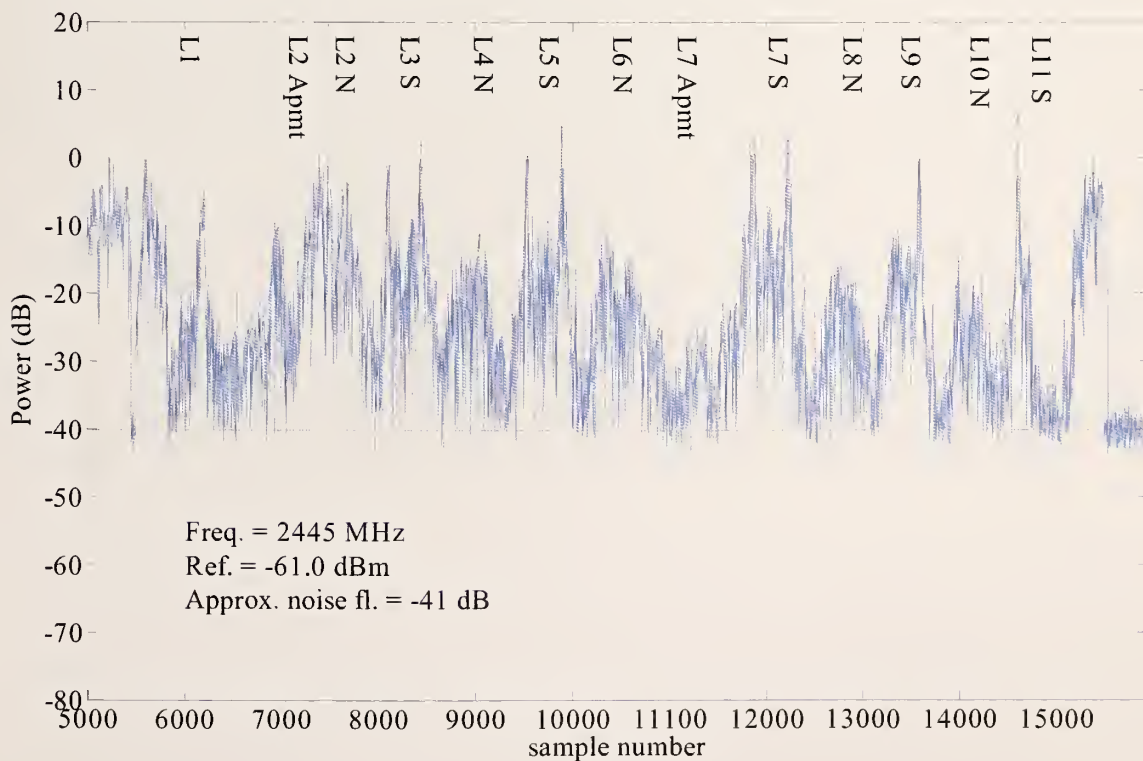


Figure 209. Boulder, CO apartment walk-through at 2445 MHz; receiver at site 2.



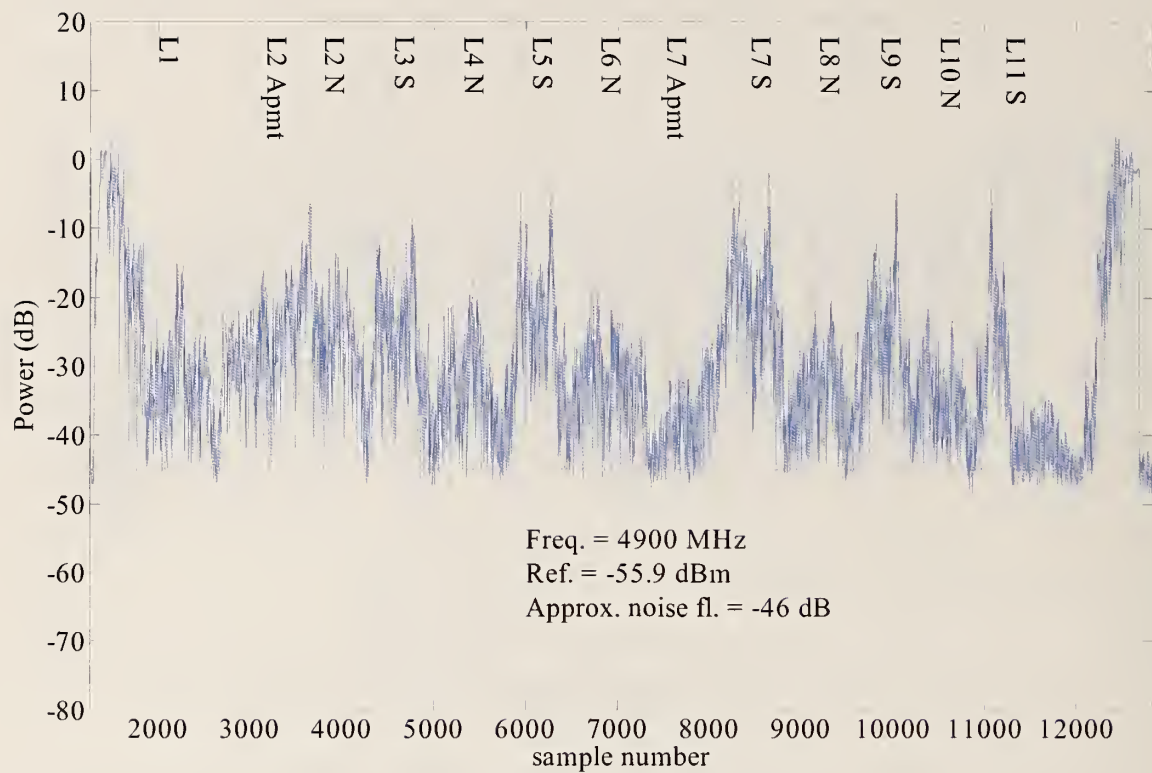


Figure 210. Boulder, CO apartment walk-through at 4900 MHz; receiver at site 2.

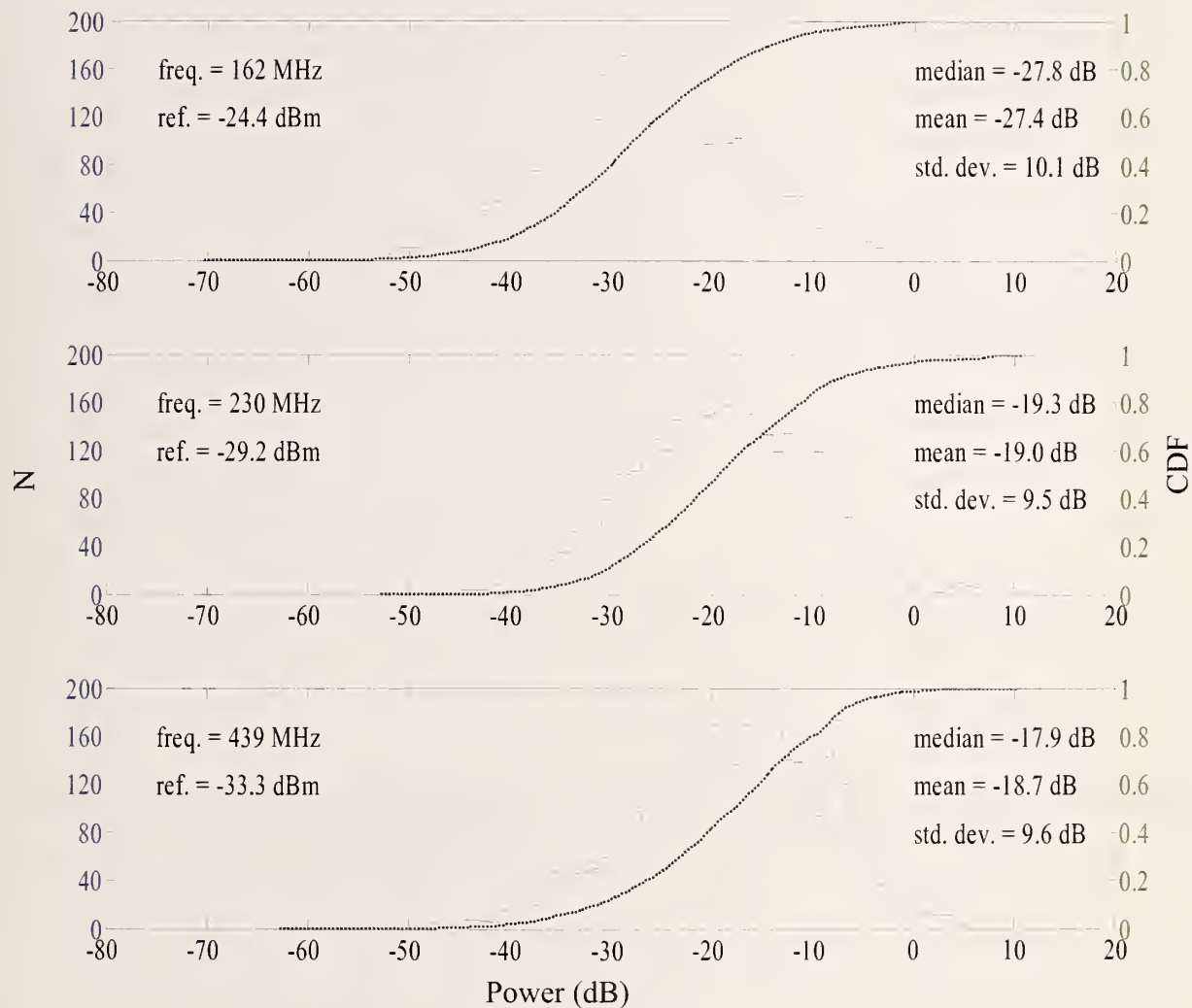


Figure 211. Boulder, CO apartment walk-through statistics, histograms, and empirical CDF for walk-through data with the receiver at site 2; 162.075, 230.0, and 439.25 MHz.

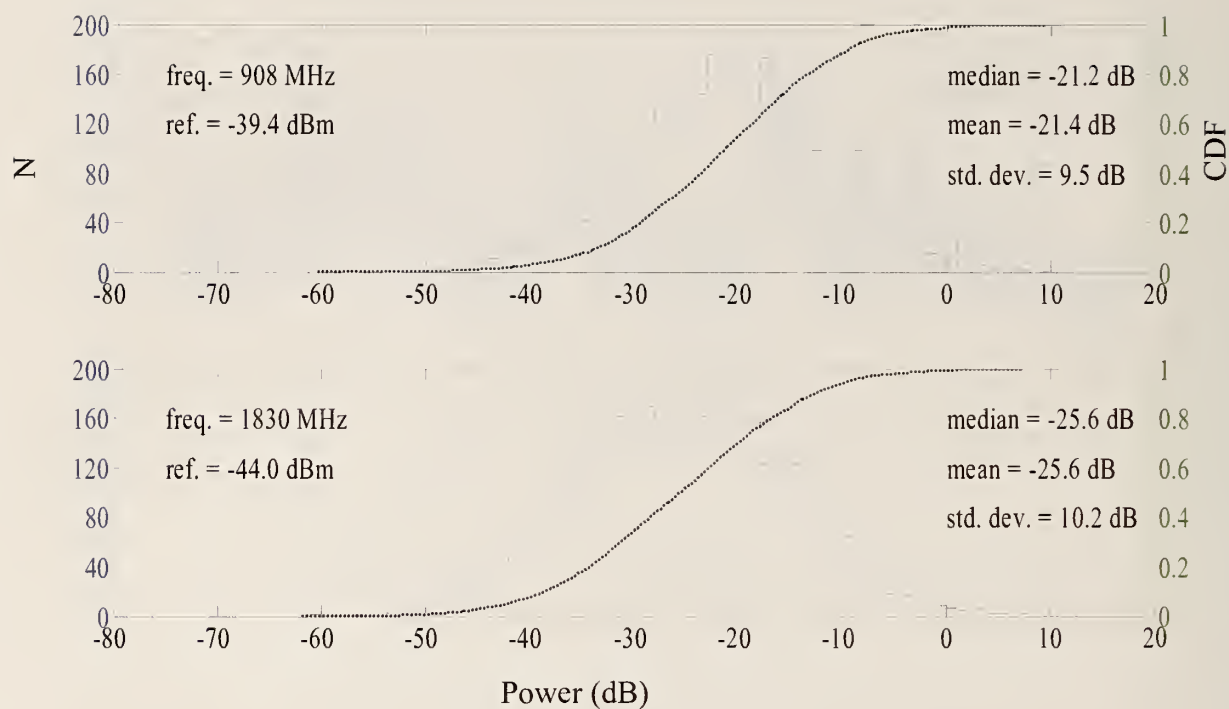


Figure 212. Boulder, CO apartment walk-through statistics, histograms, and empirical CDF for walk-through data with the receiver at site 2; 908.0 and 1830.0 MHz.

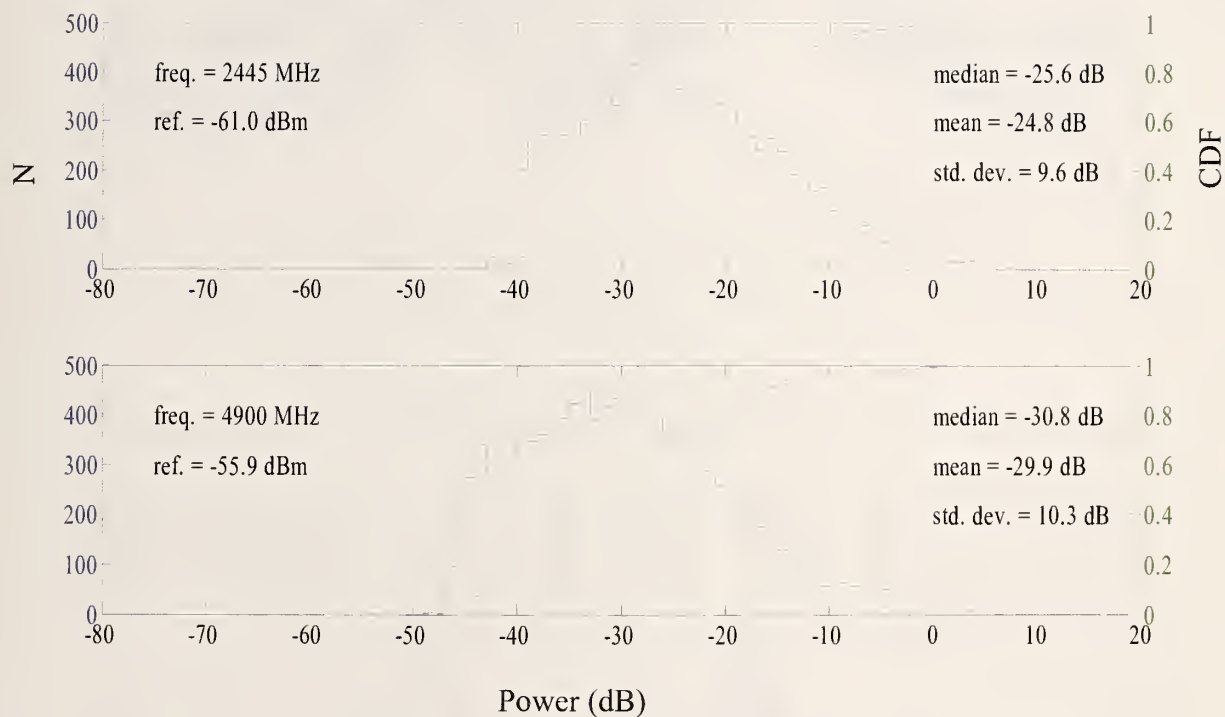


Figure 213. Boulder, CO apartment walk-through statistics, histograms, and empirical CDF for walk-through data with the receiver at site 2; 2445 and 4900 MHz.



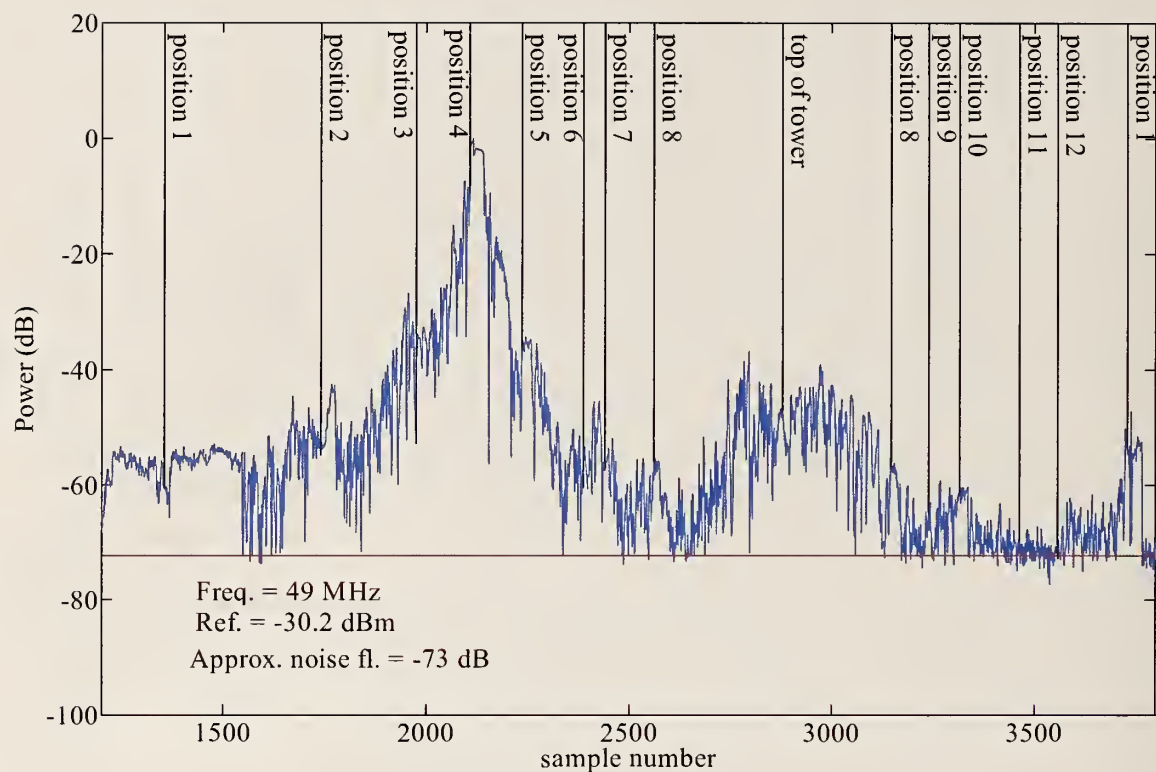


Figure 214. SUNCOR oil refinery walk-through at 49.85 MHz; receiver at south site.

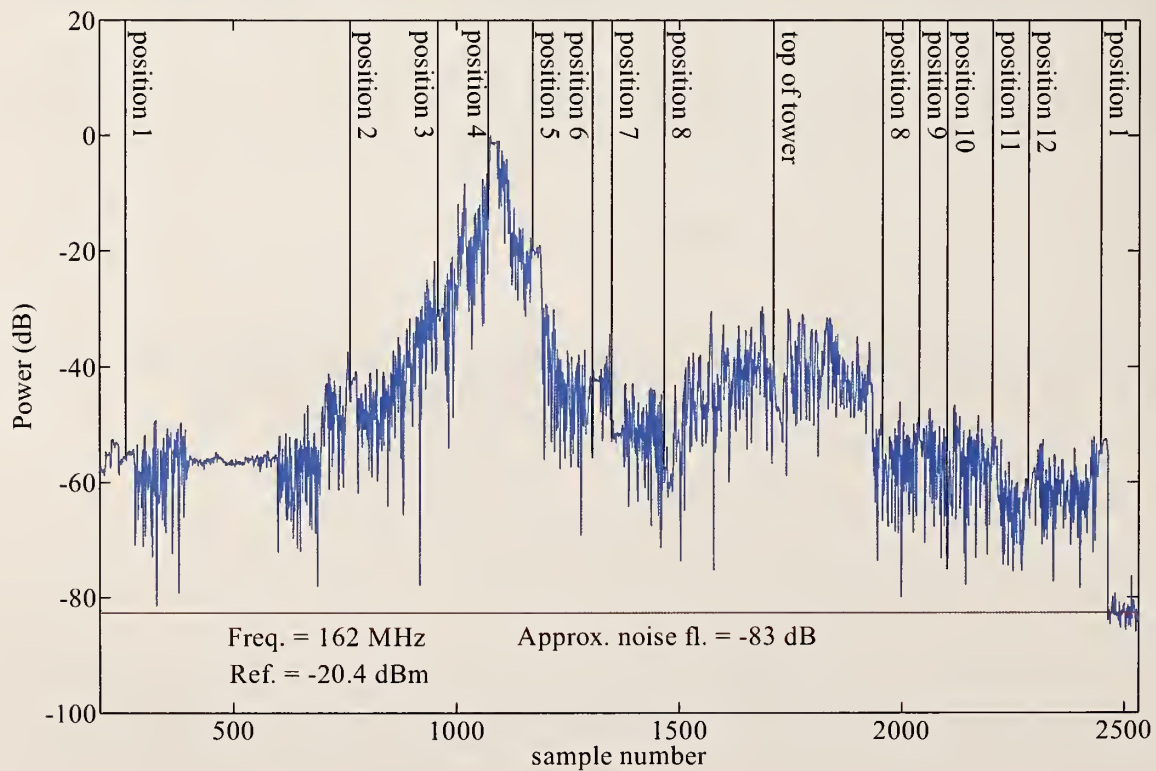


Figure 215. SUNCOR oil refinery walk-through at 162.075 MHz; receiver at south site.

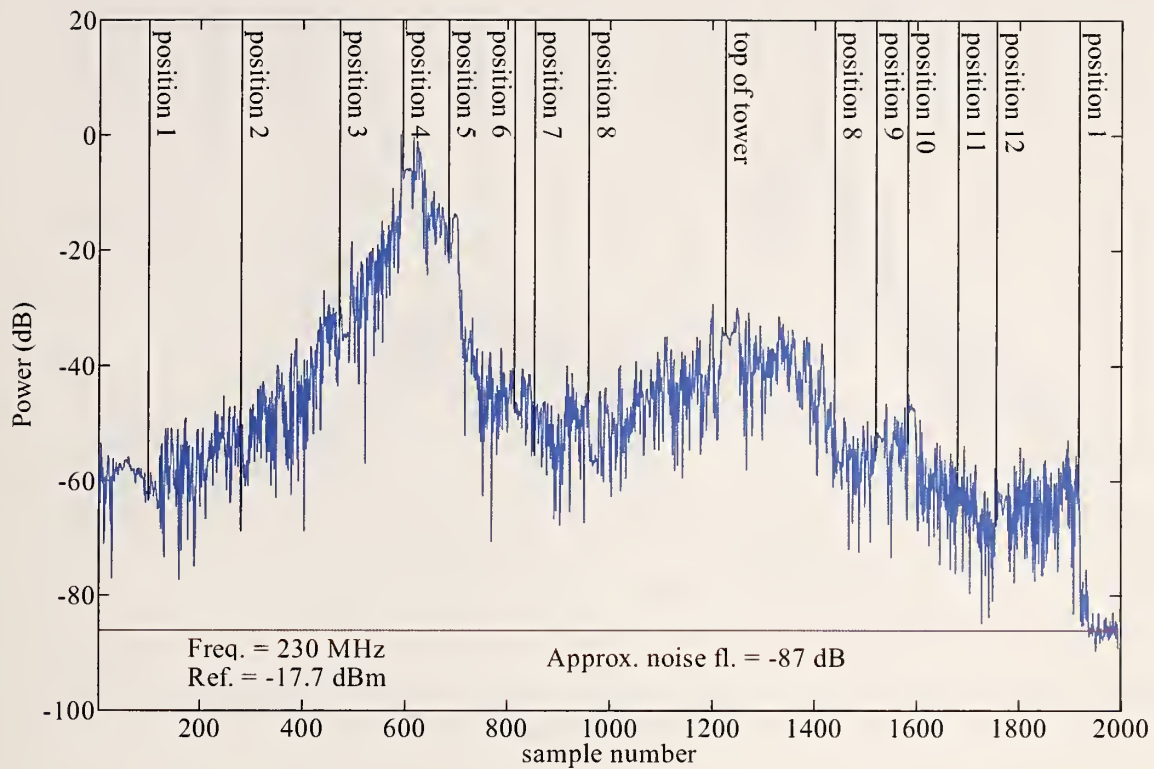


Figure 216. SUNCOR oil refinery walk-through at 230.0 MHz; receiver at south site.

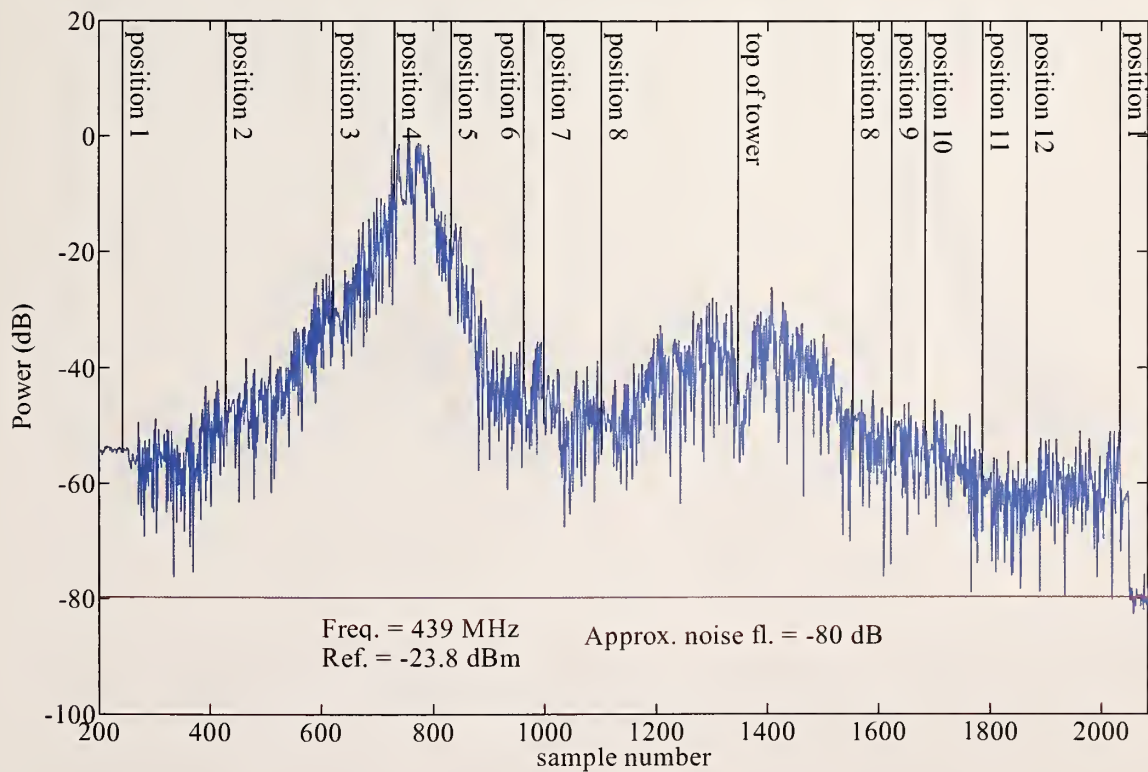


Figure 217. SUNCOR oil refinery walk-through at 439.25 MHz; receiver at south site.

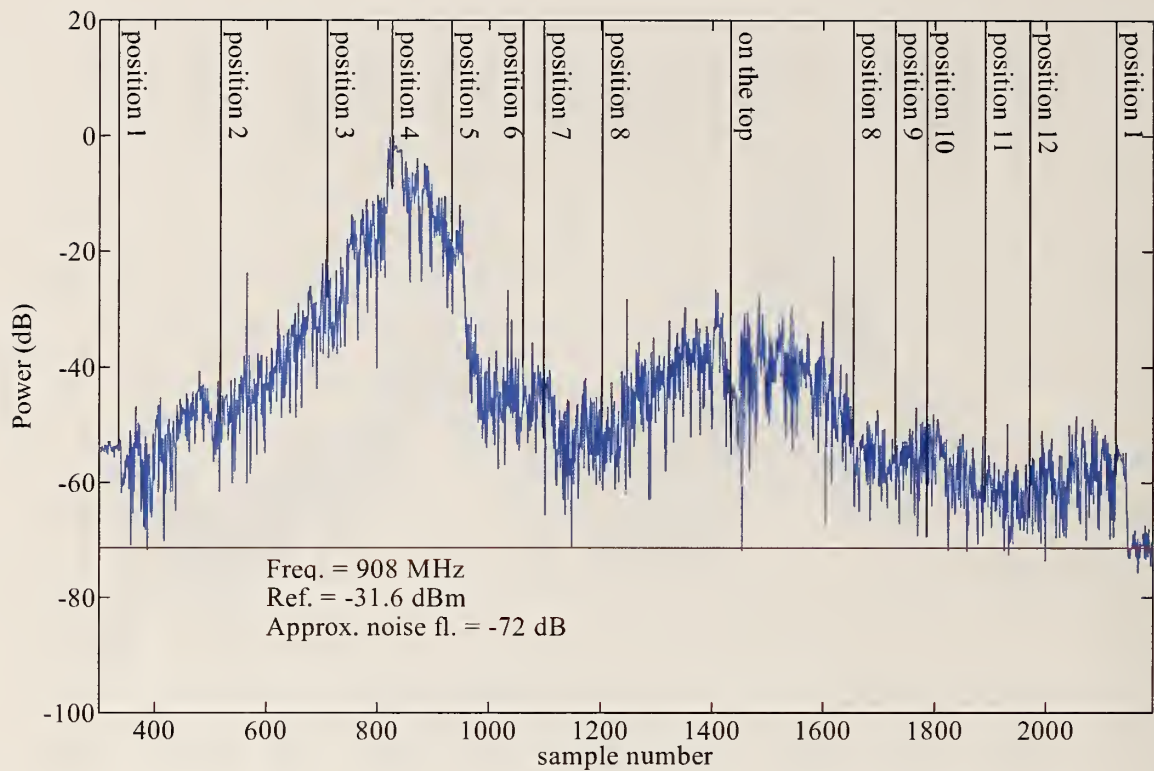


Figure 218. SUNCOR oil refinery walk-through at 908.0 MHz; receiver at south site.

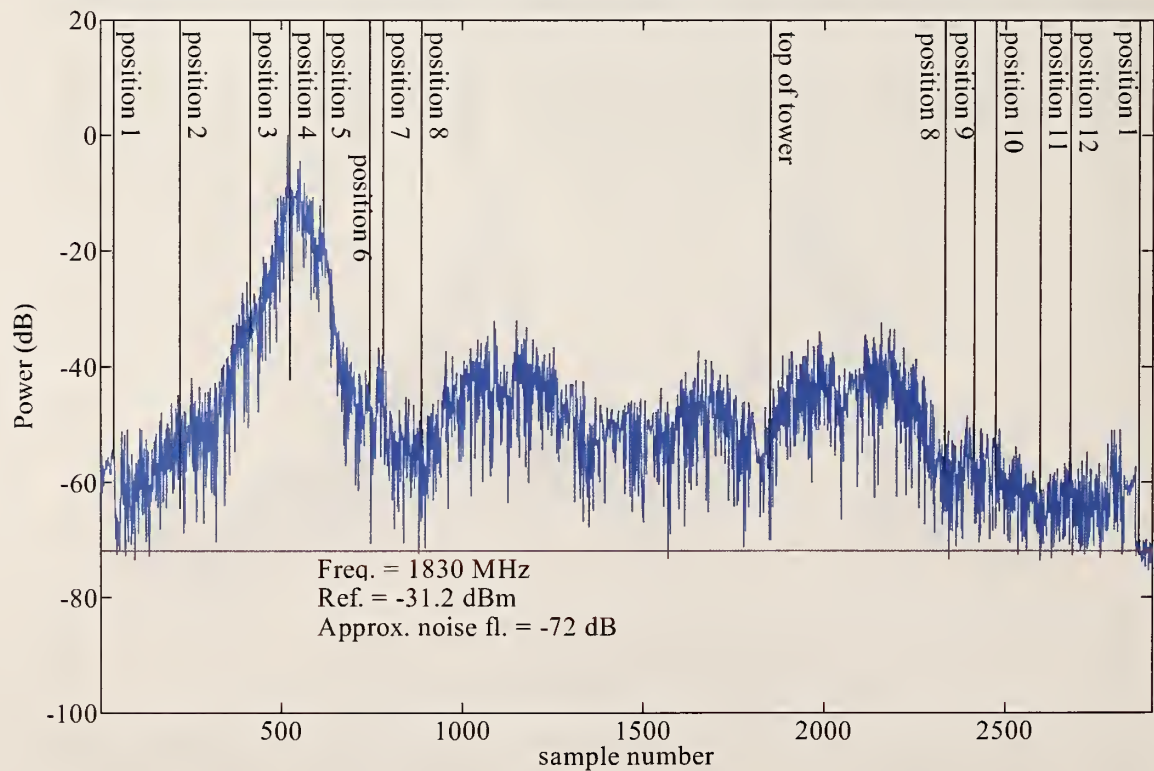


Figure 219. SUNCOR oil refinery walk-through at 1830.1 MHz; receiver at south site.

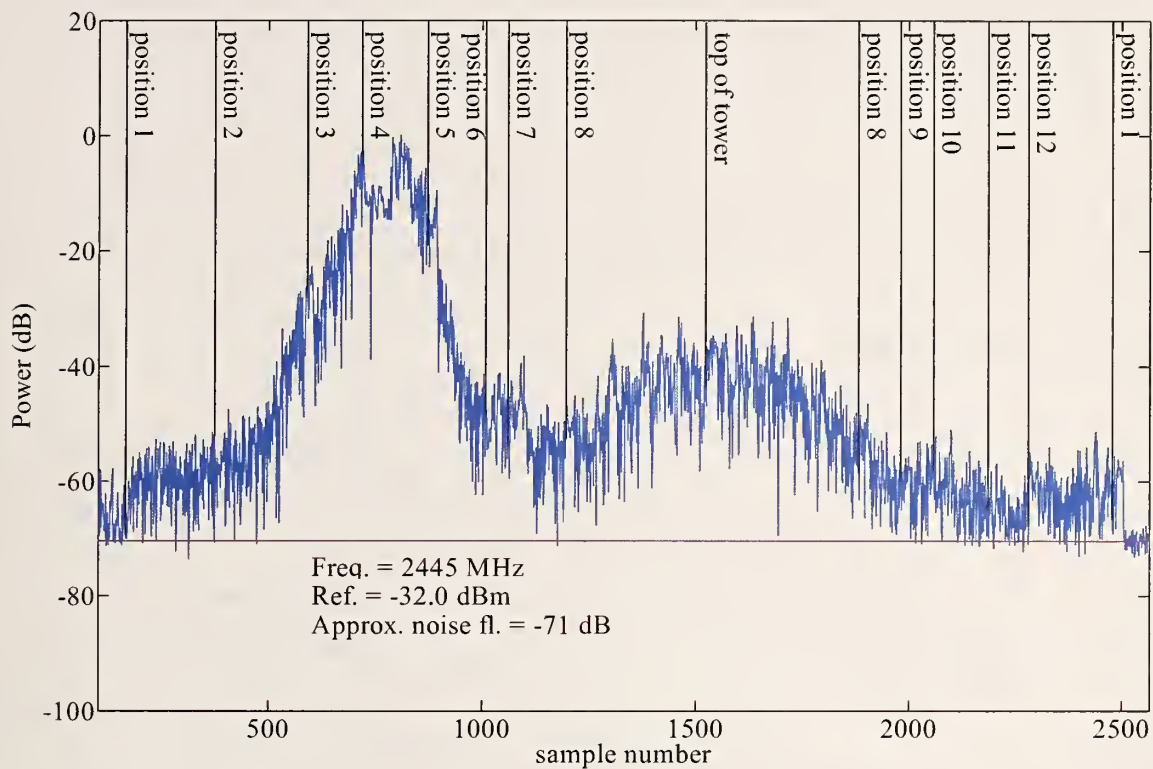


Figure 220. SUNCOR oil refinery walk-through at 2445.0 MHz.

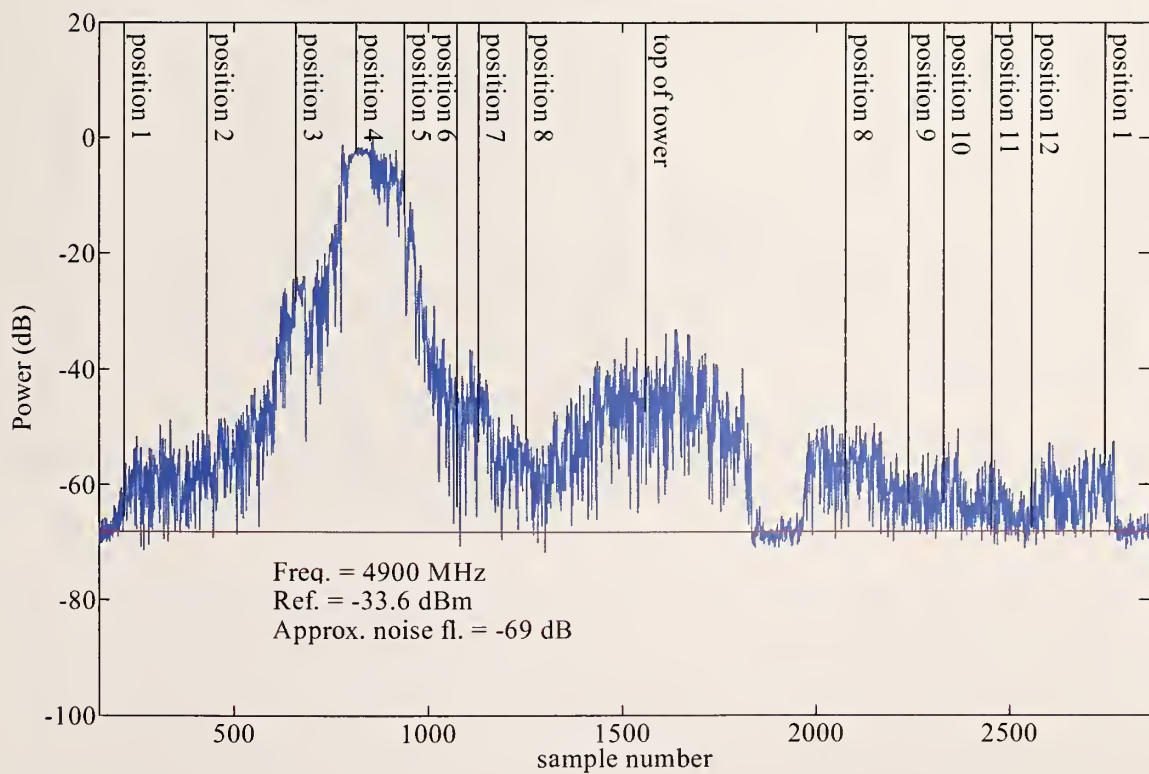


Figure 221. SUNCOR oil refinery walk-through at 4900.0 MHz; receiver at south site.



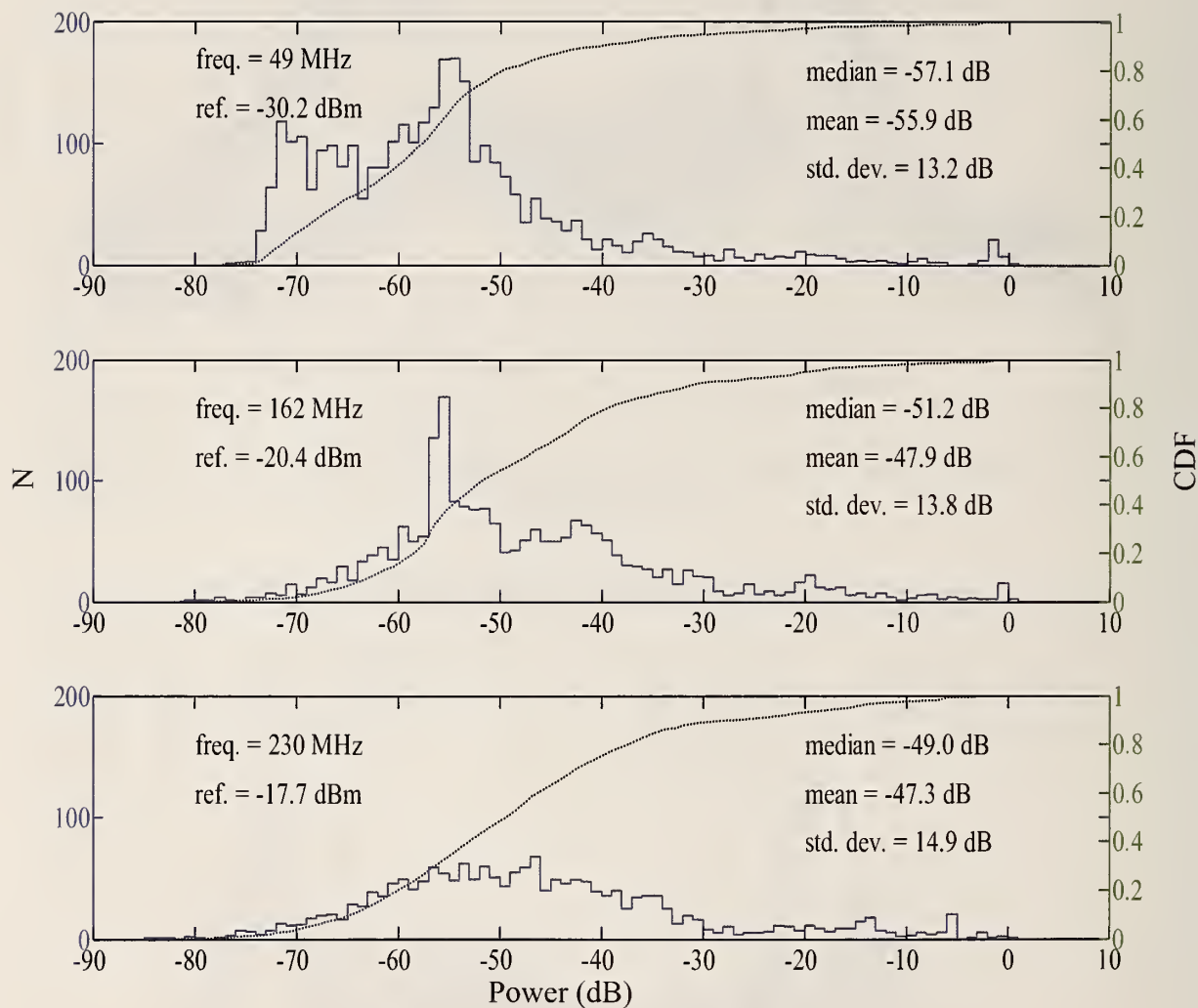


Figure 222. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 49.85, 162.075, and 230.0 MHz; receiver at south site.

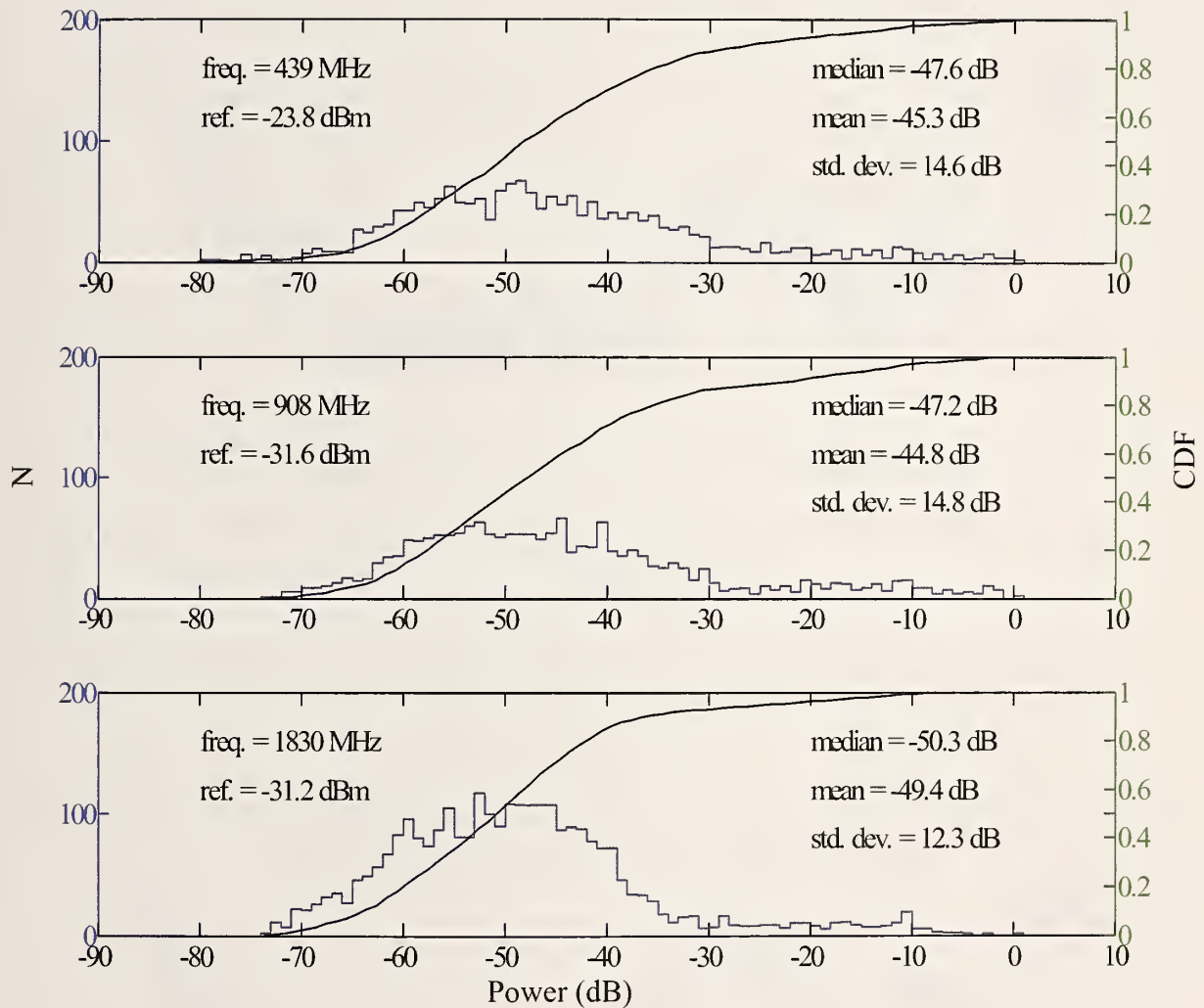


Figure 223. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 439.25, 908.0, and 1830.1 MHz; receiver at south site.

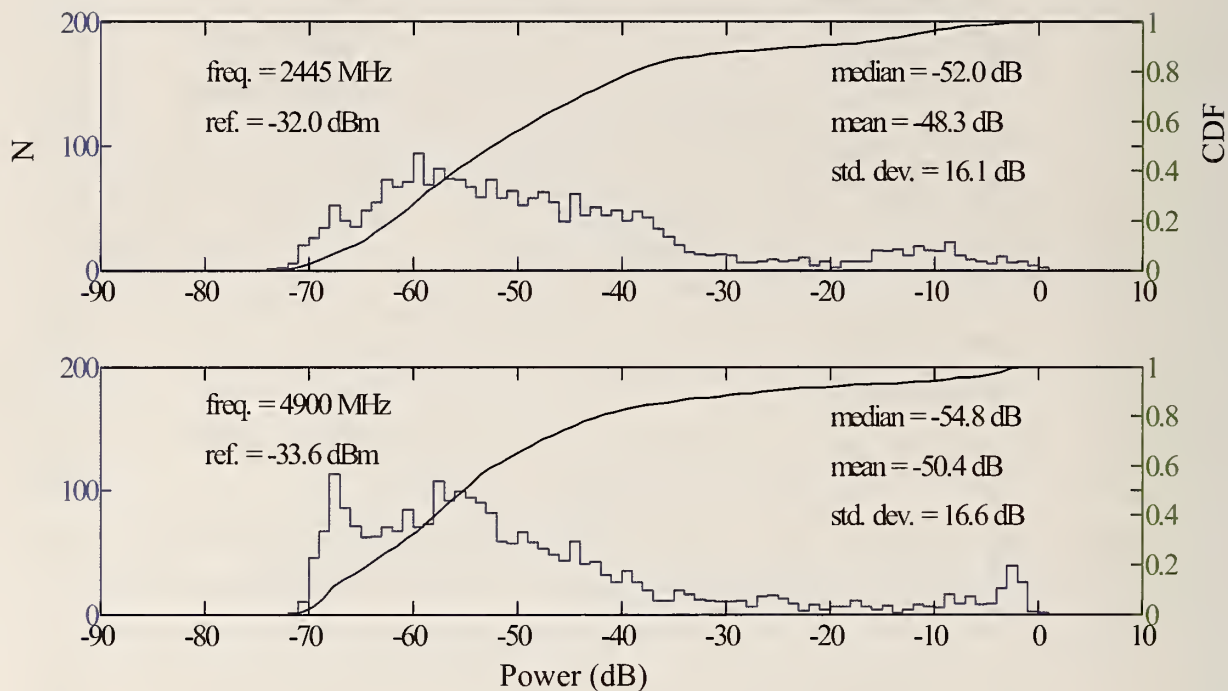


Figure 224. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 2445.0 and 4900.0 MHz; receiver at south site.

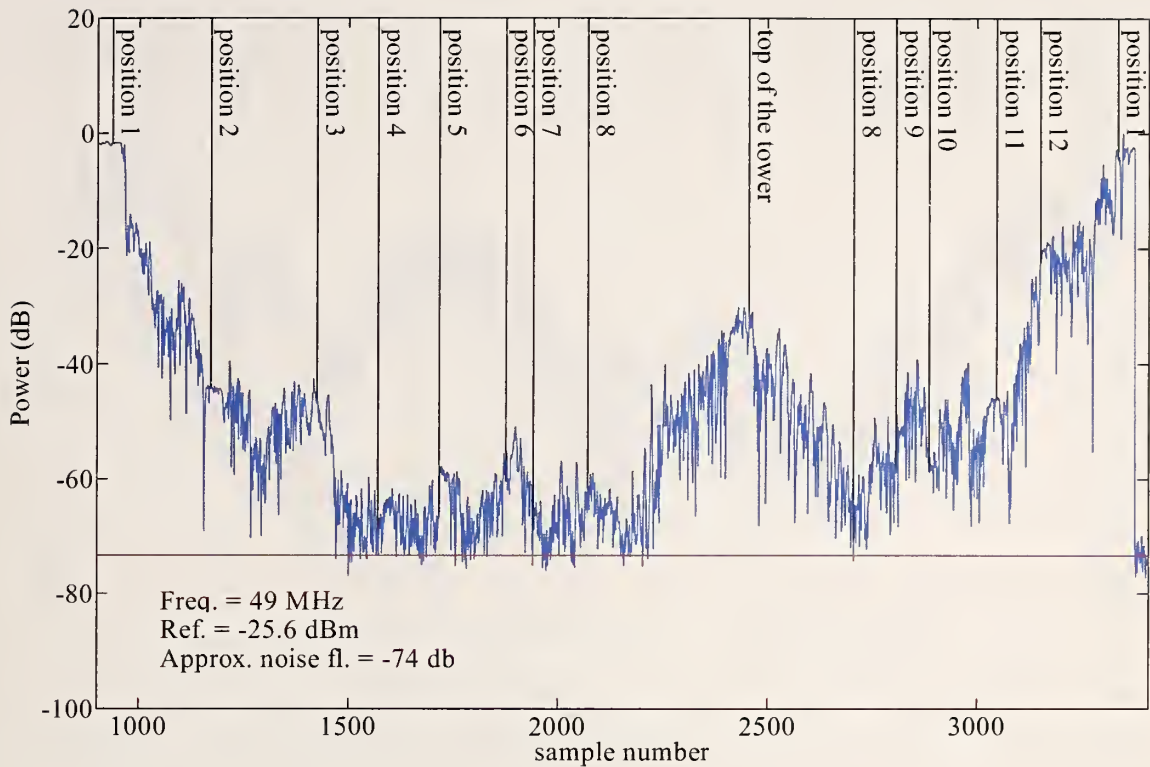


Figure 225. SUNCOR oil refinery walk-through at 49.85 MHz; receiver at north site.

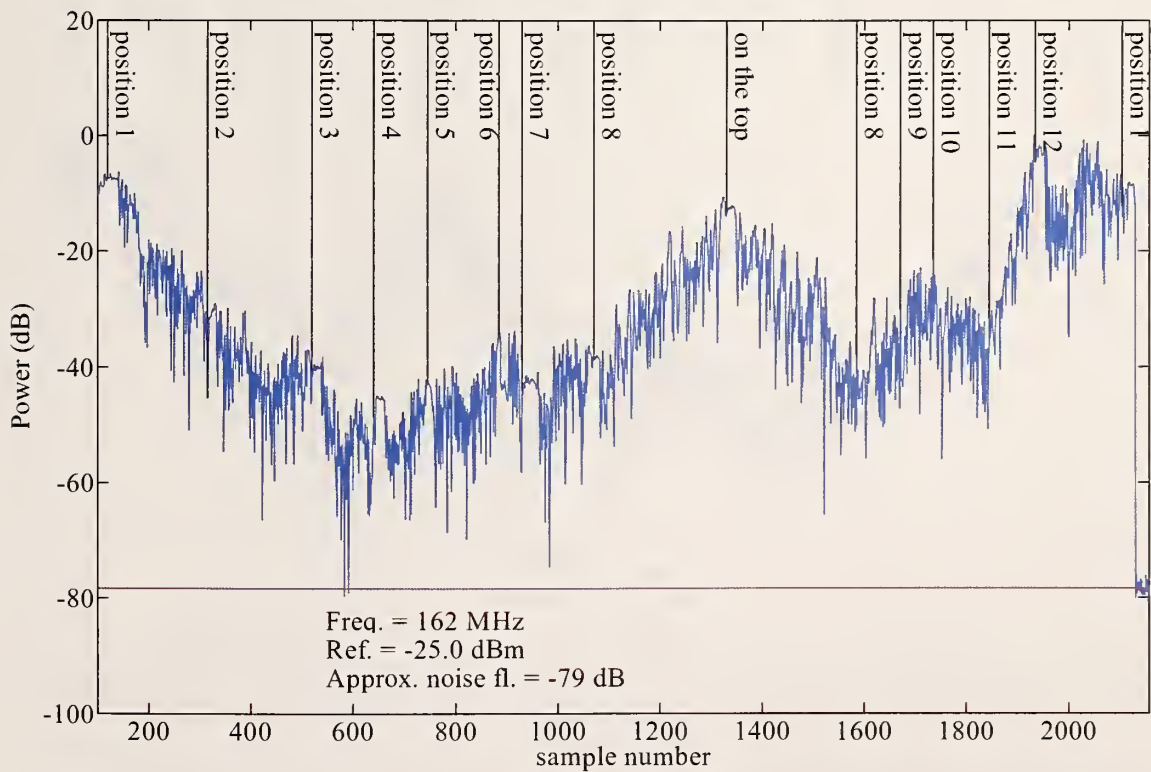


Figure 226. SUNCOR oil refinery walk-through at 162.075 MHz; receiver at north site.



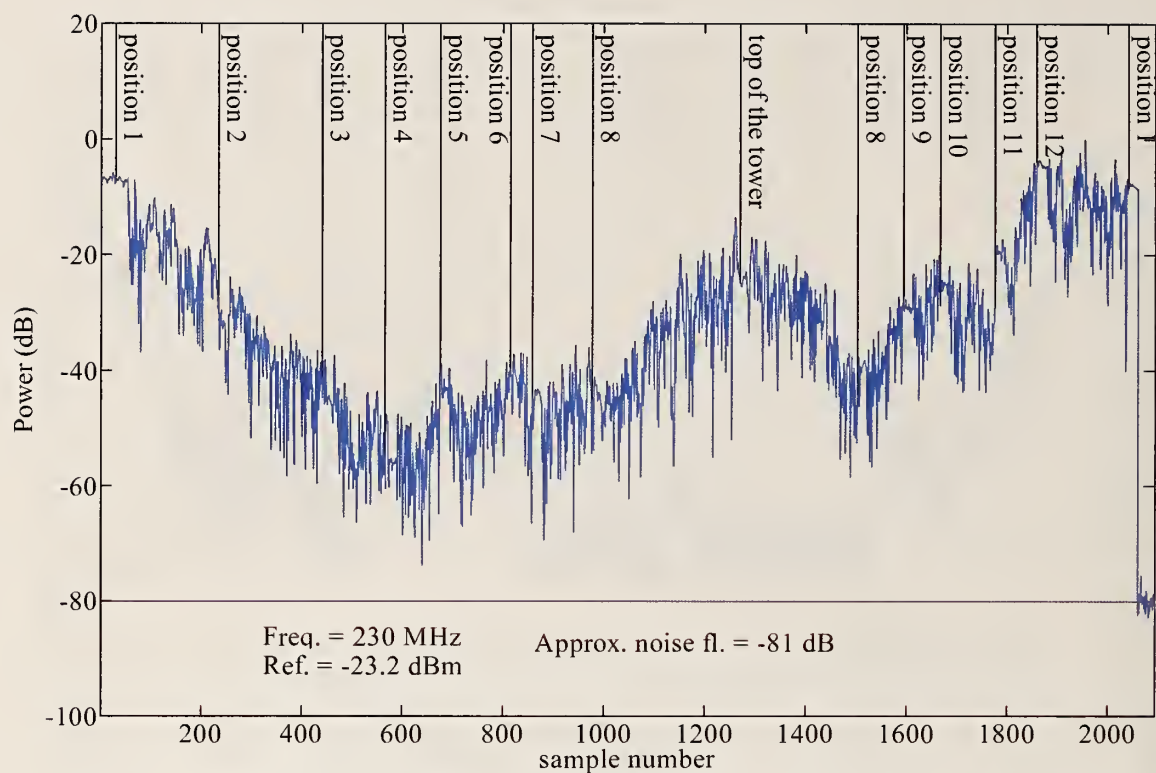


Figure 227. SUNCOR oil refinery walk-through at 230.0 MHz; receiver at north site.

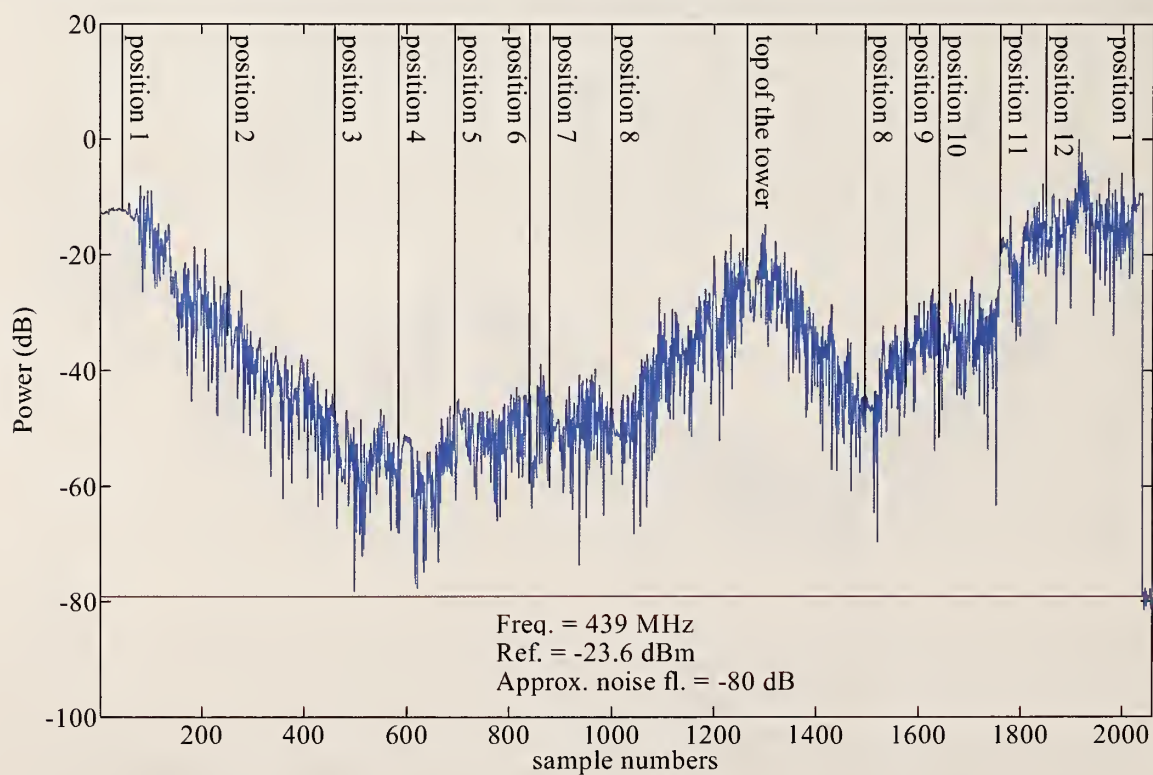


Figure 228. SUNCOR oil refinery walk-through at 439.25 MHz; receiver at north site.

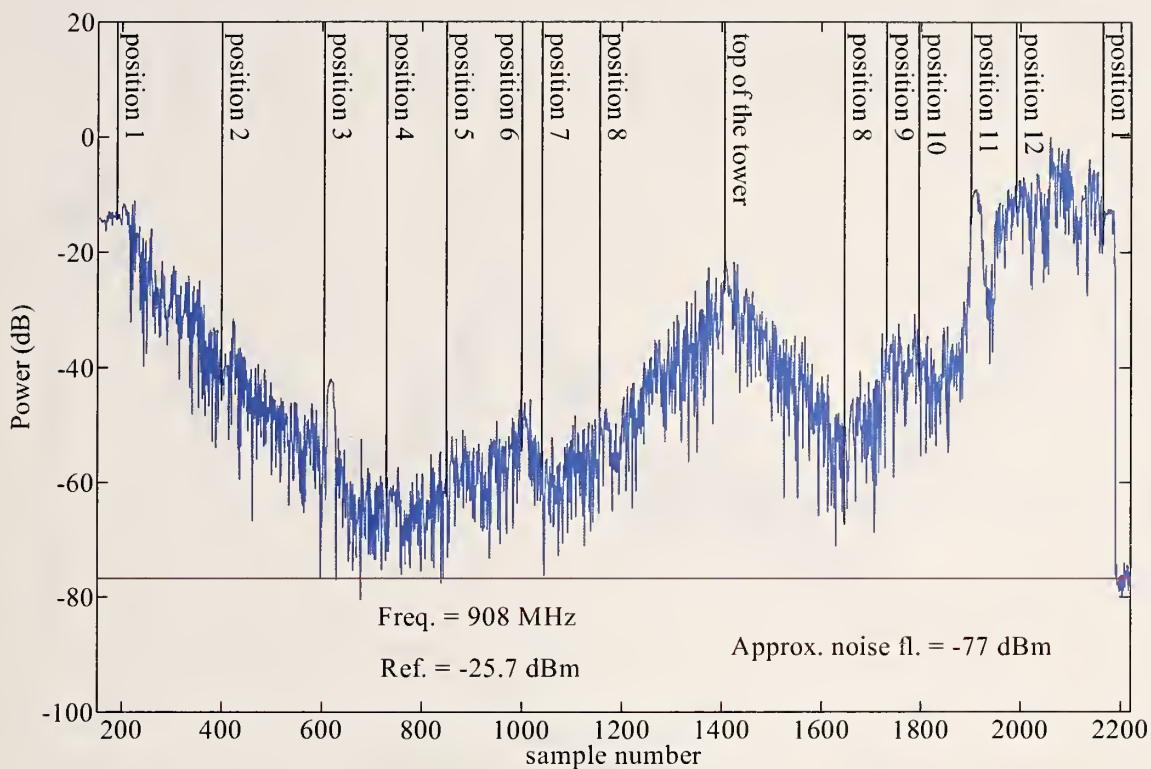


Figure 229. SUNCOR oil refinery walk-through at 908.0 MHz; receiver at north site.

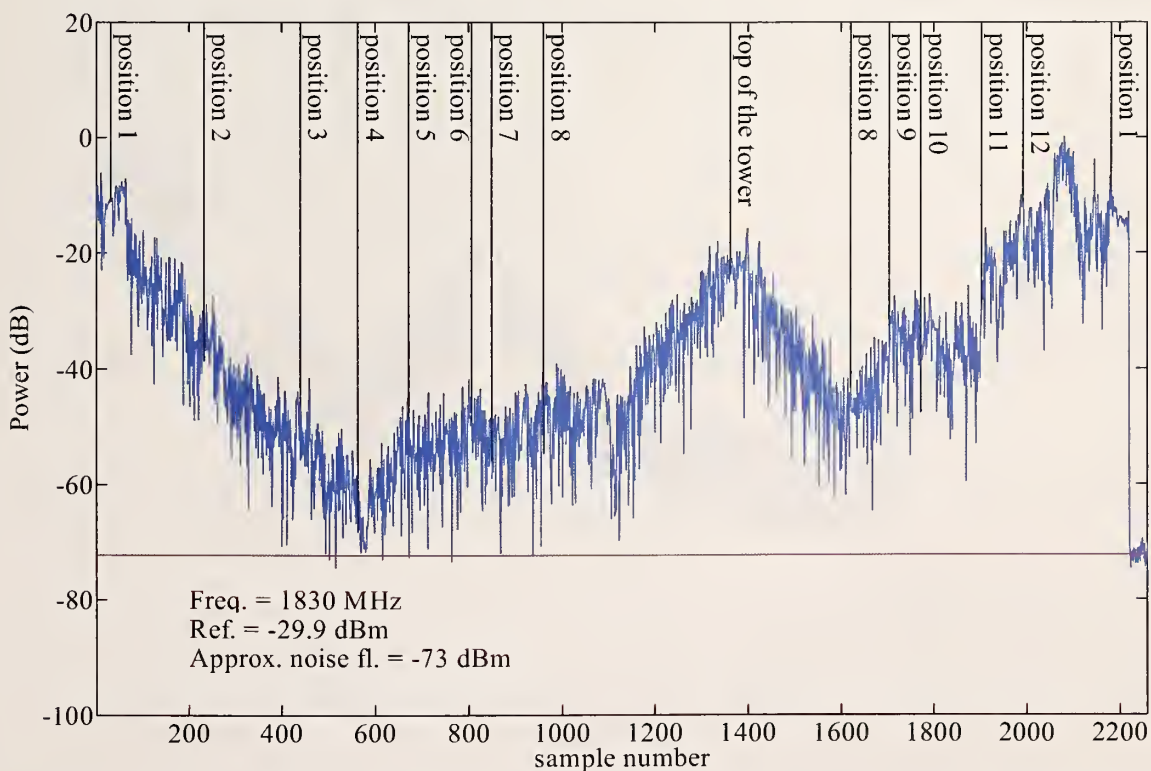


Figure 230. SUNCOR oil refinery walk-through at 1830.1 MHz; receiver at north site.

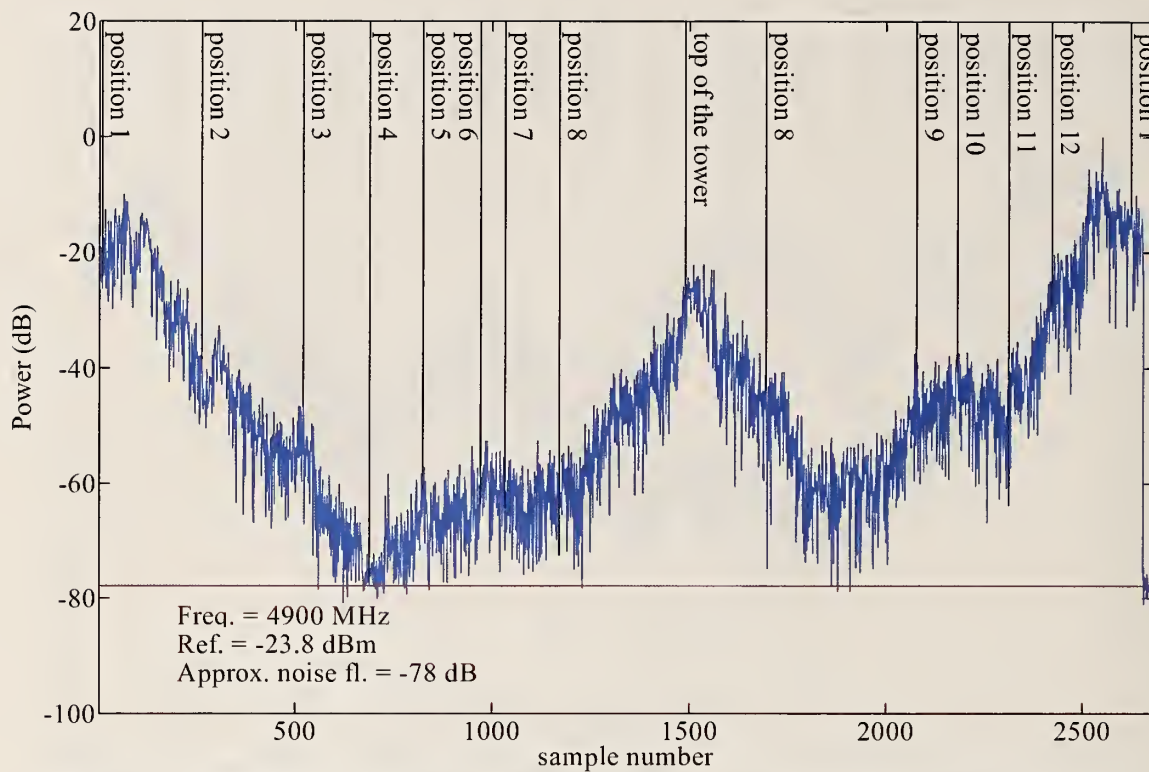


Figure 231. SUNCOR oil refinery walk-through at 2445.0 MHz; receiver at north site.

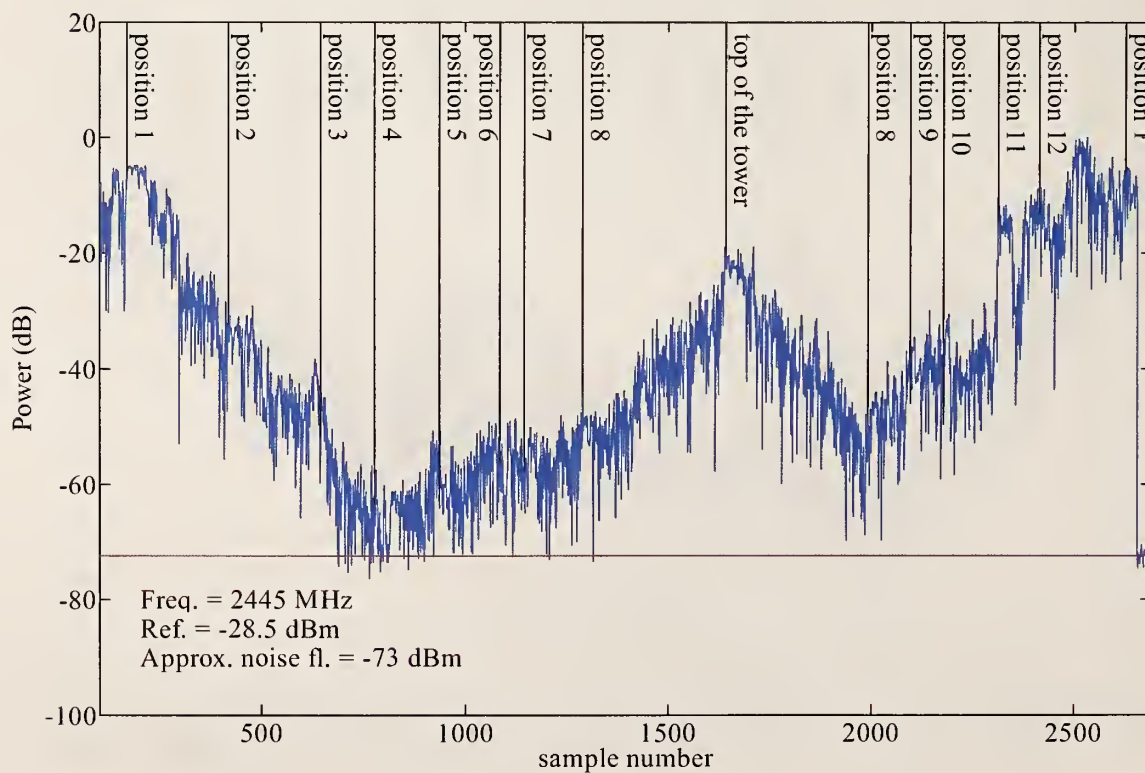


Figure 232. SUNCOR oil refinery walk-through at 4900.0 MHz; receiver at north site.

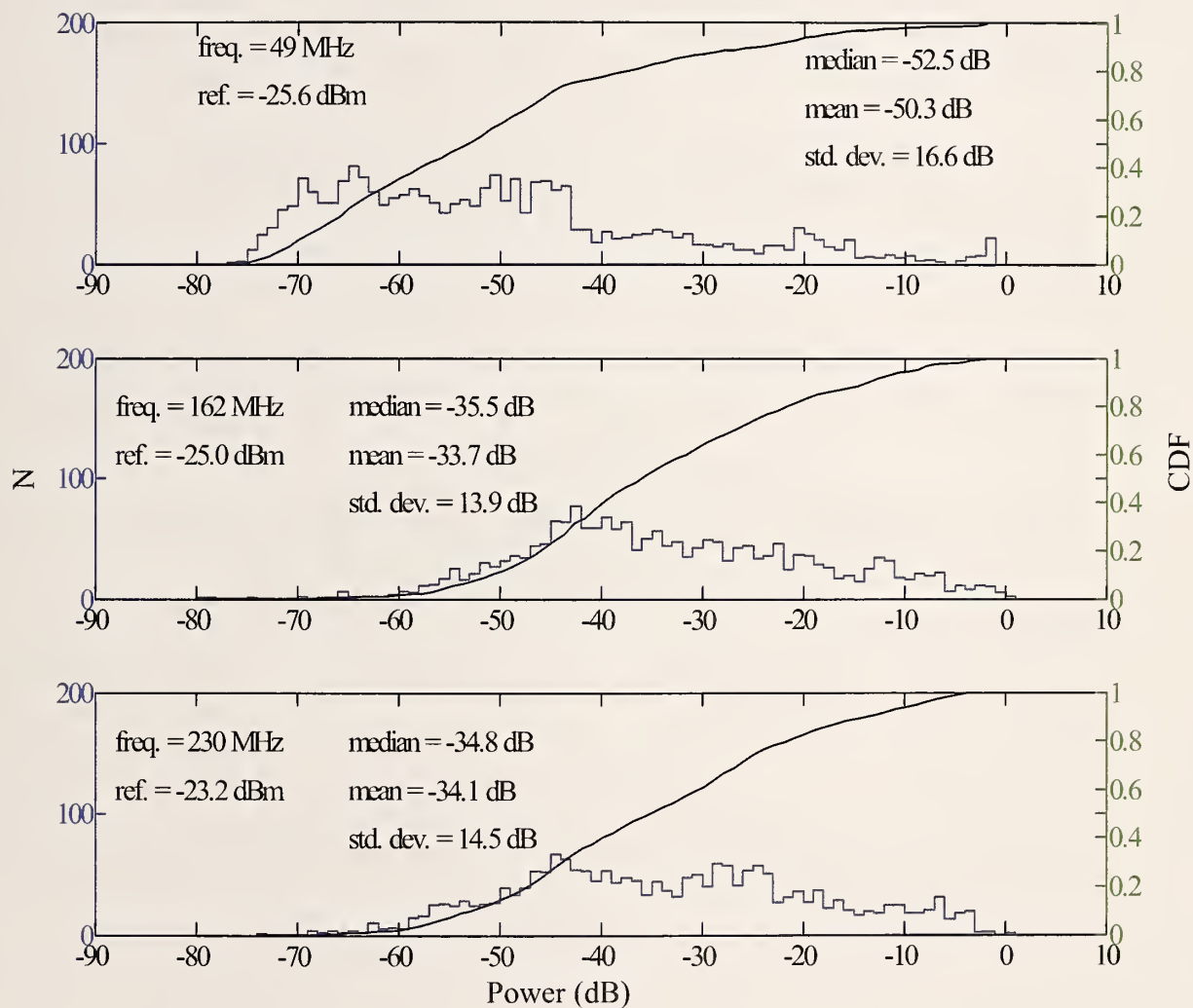


Figure 233. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 49.85, 162.075, and 230.0 MHz; receiver at north site.



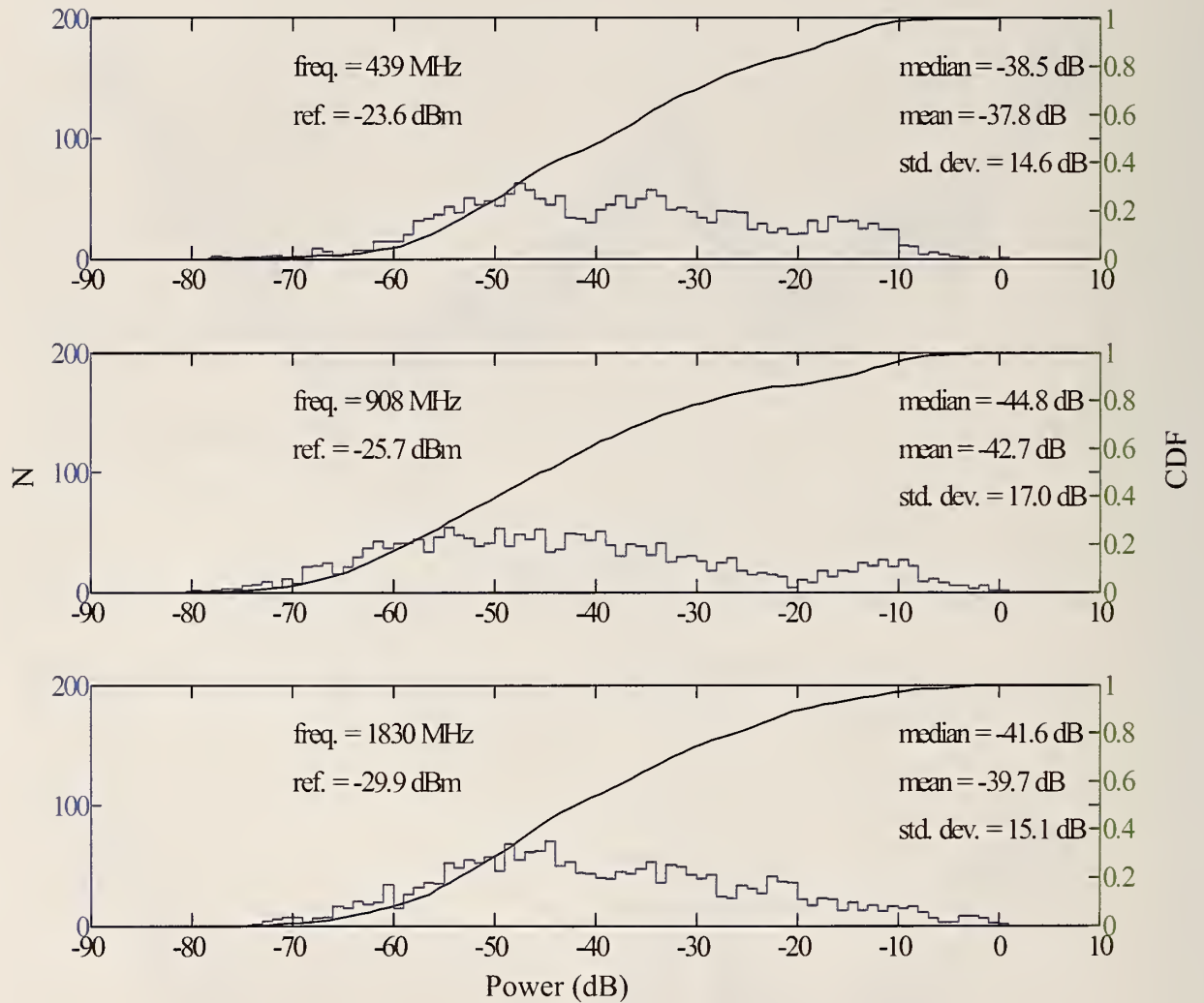


Figure 234. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 439.25, 908.0, and 1830.1 MHz; receiver at north site.

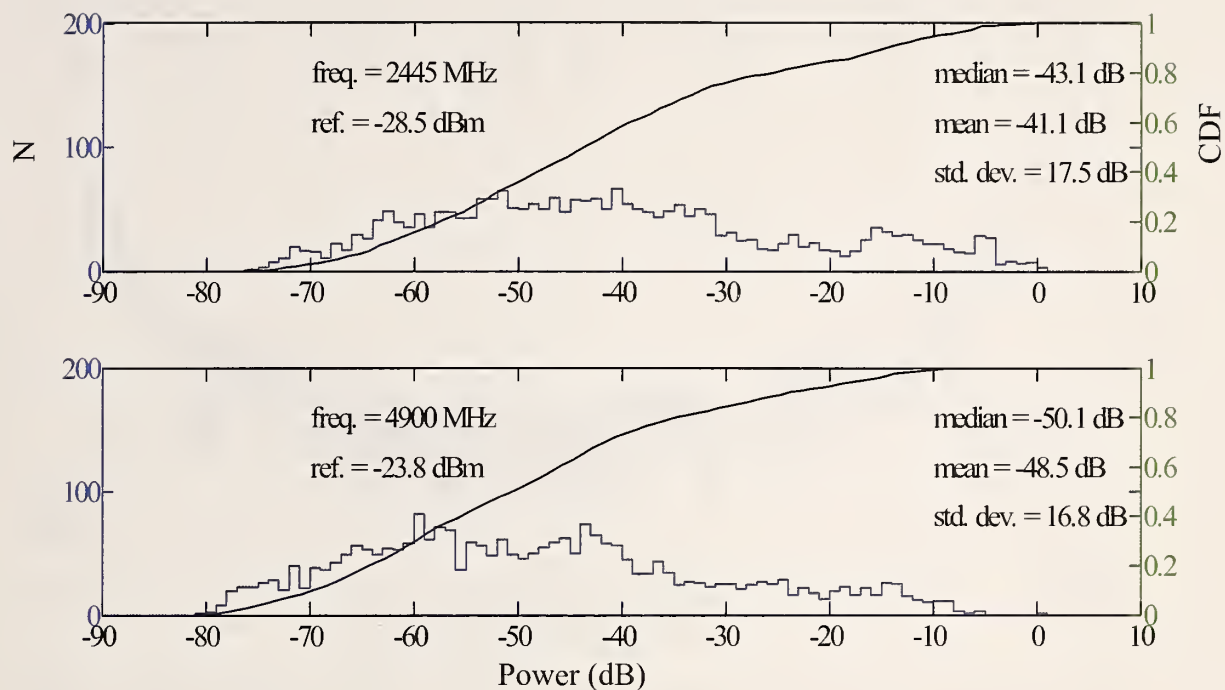


Figure 235. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 2445.0 and 4900.0 MHz; receiver at north site.

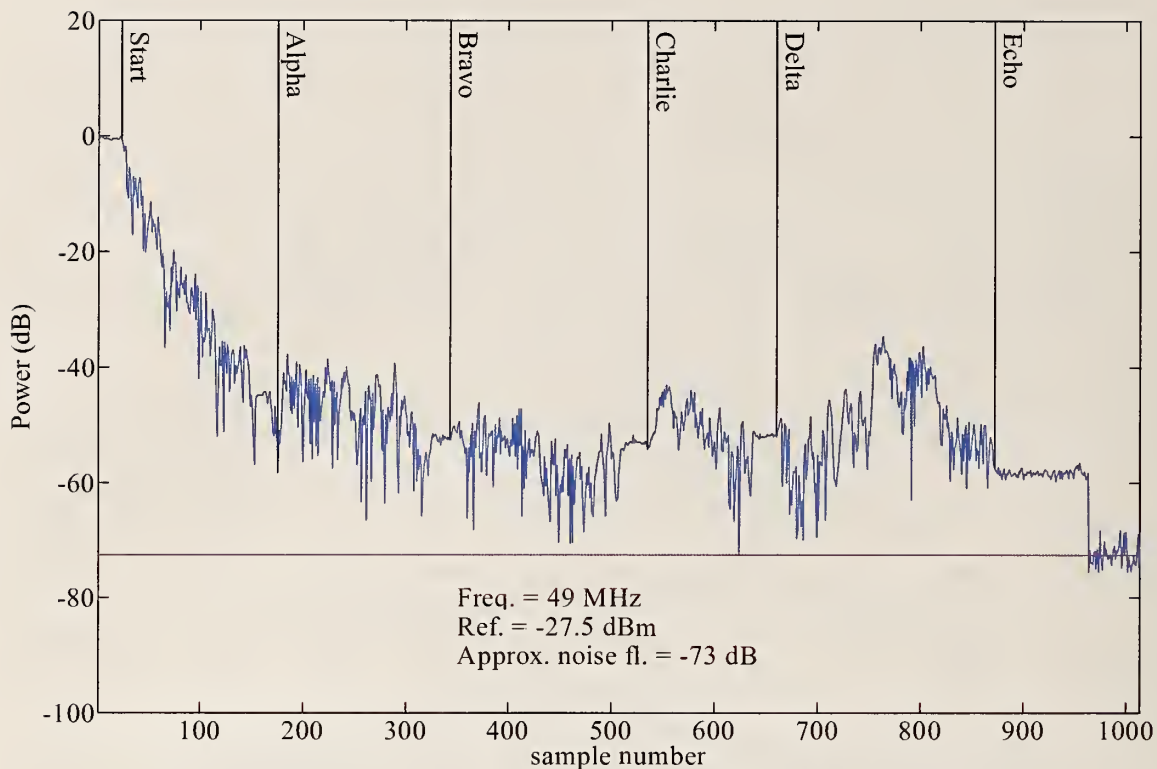


Figure 236. SUNCOR oil refinery road drive at 49.85 MHz; receiver at north site.

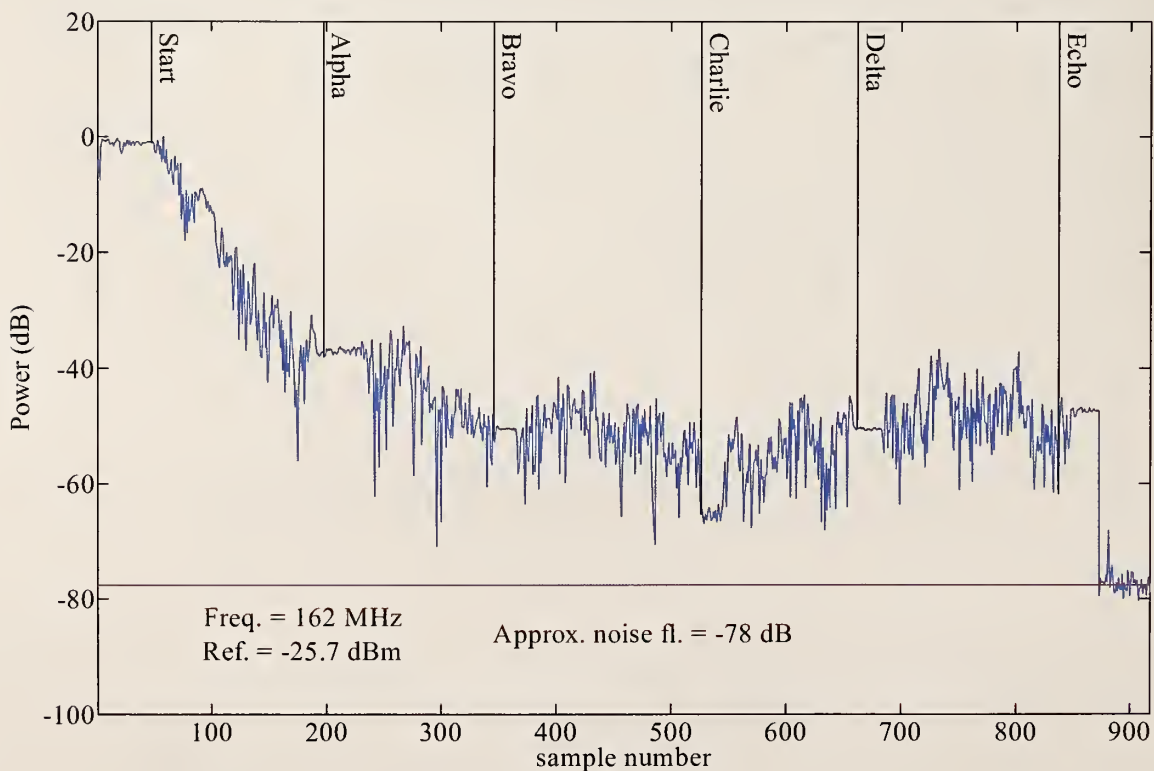


Figure 237. SUNCOR oil refinery road drive at 162.075 MHz; receiver at north site.

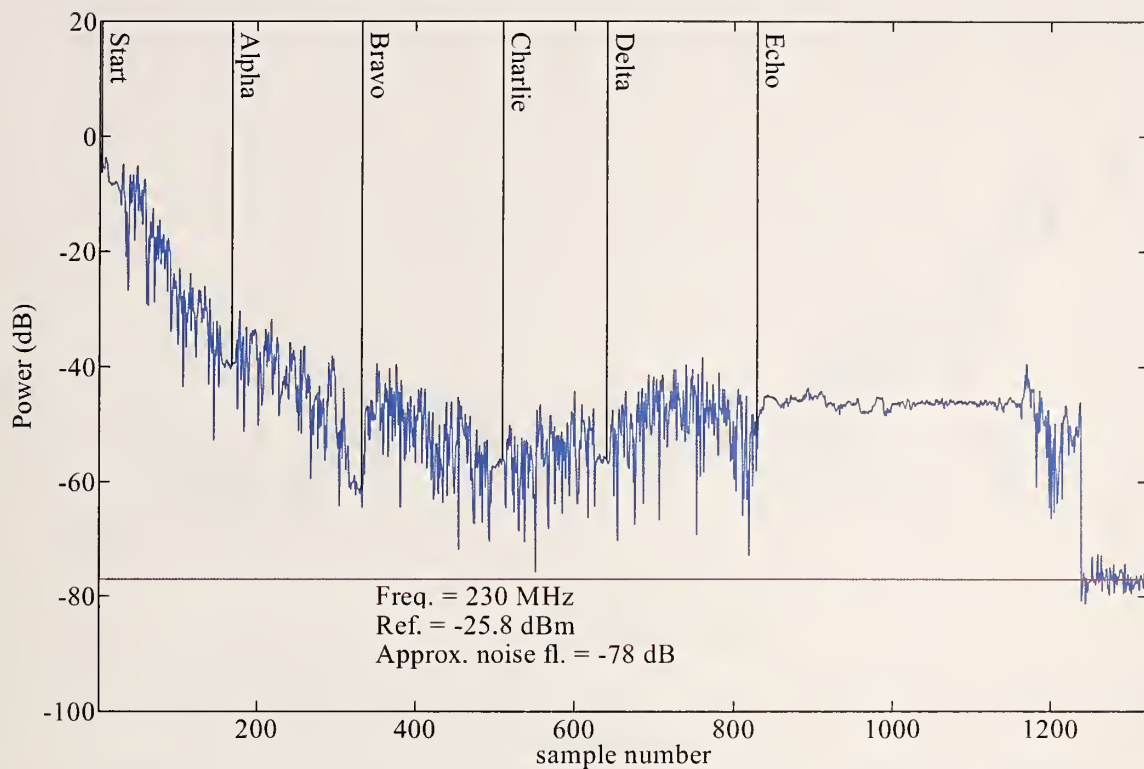


Figure 238. SUNCOR oil refinery road drive at 230.0 MHz; receiver at north site.

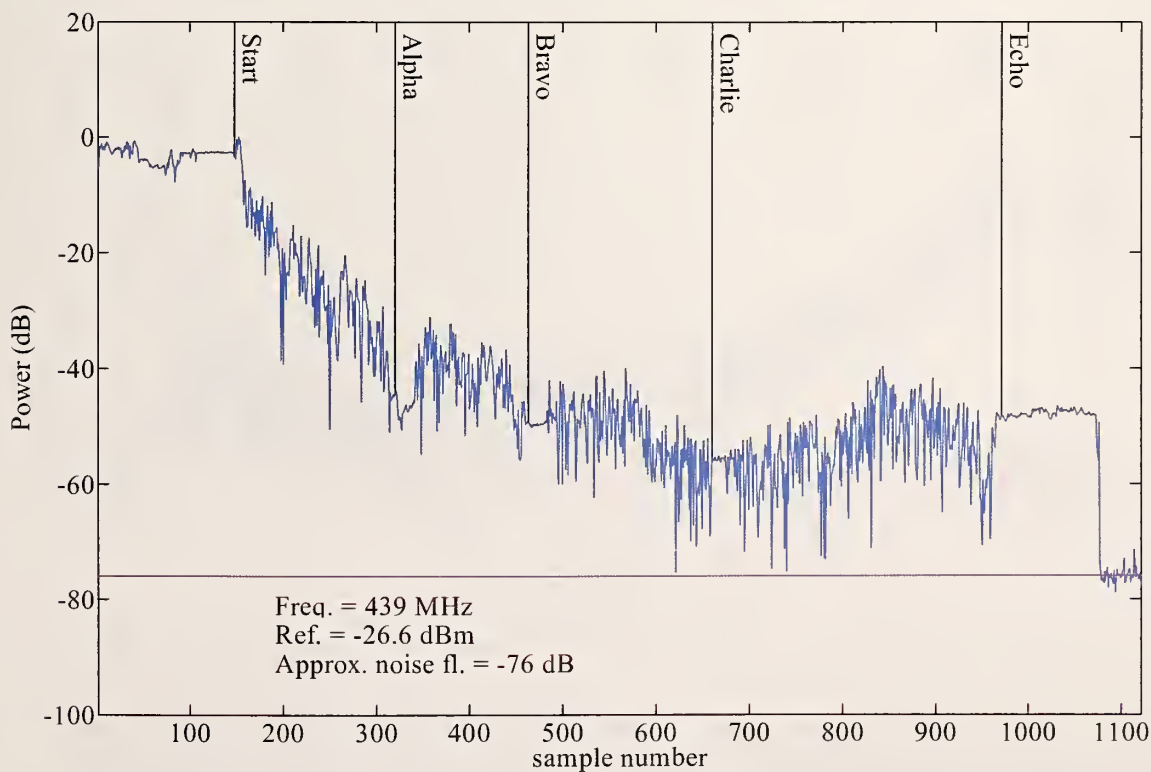


Figure 239. SUNCOR oil refinery road drive at 439.25 MHz; receiver at north site.



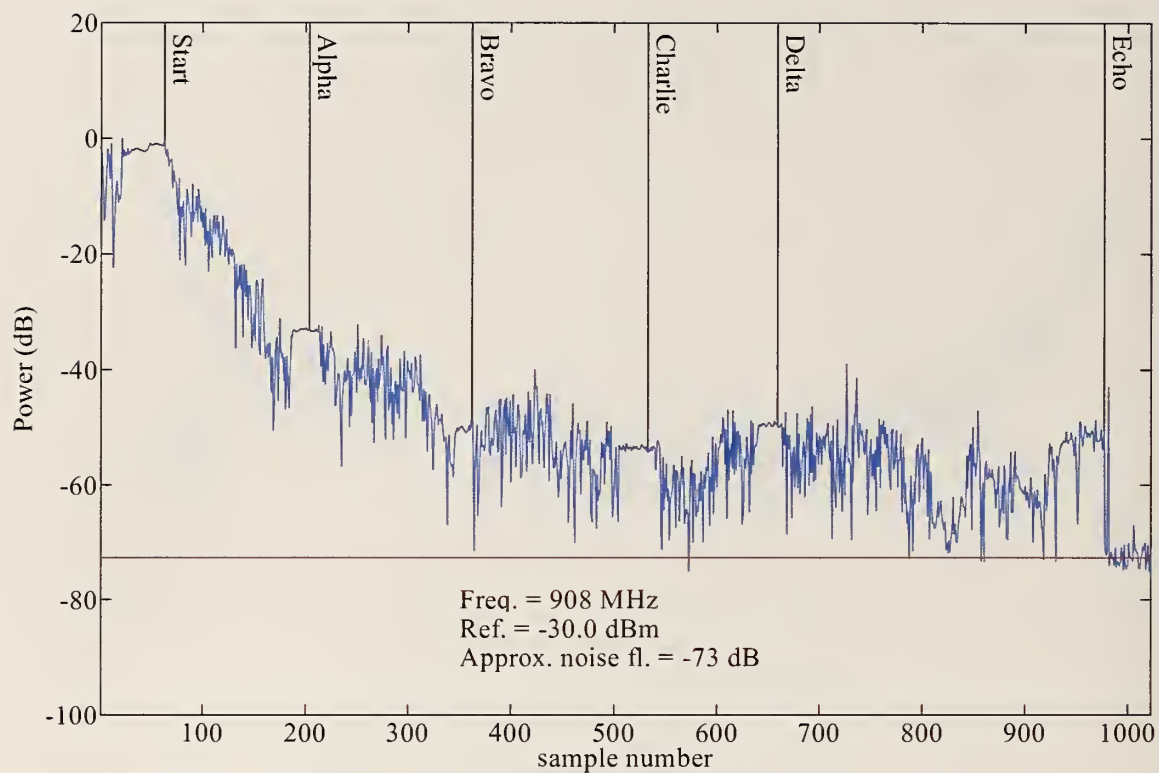


Figure 240. SUNCOR oil refinery road drive at 908.0 MHz; receiver at north site.

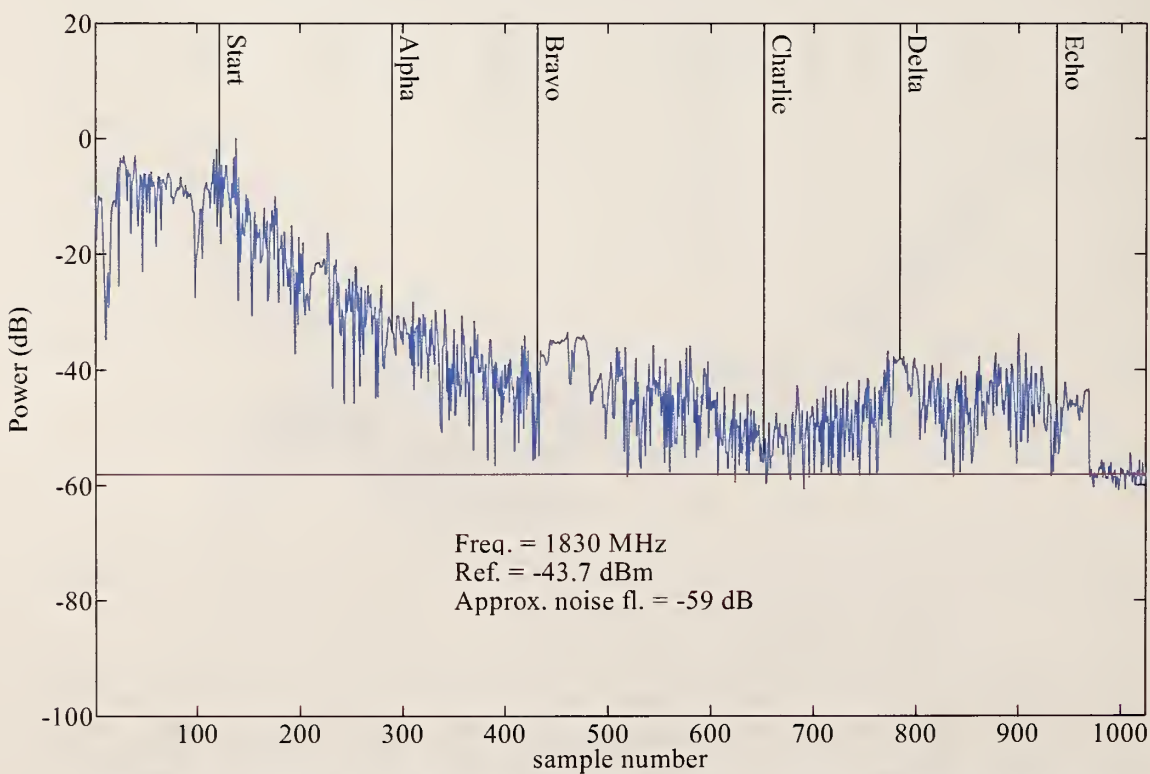


Figure 241. SUNCOR oil refinery road drive at 1830.1 MHz; receiver at north site.

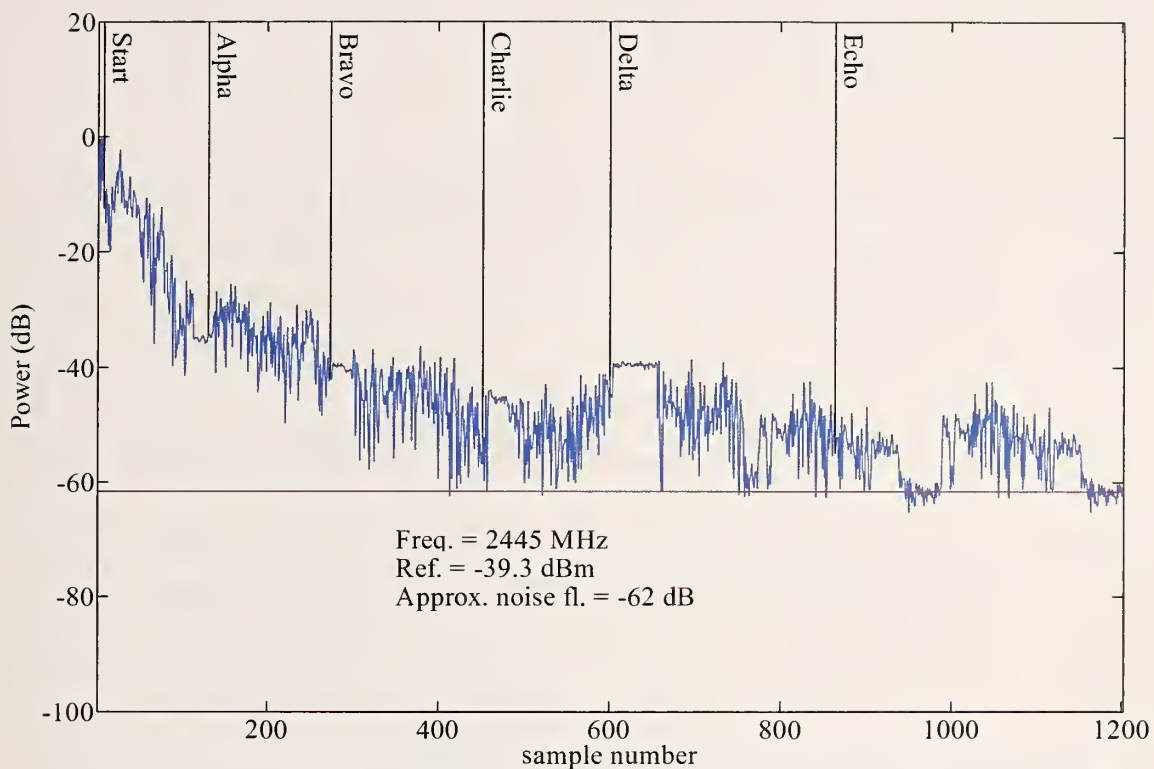


Figure 242. SUNCOR oil refinery road drive at 2445.0 MHz; receiver at north site.

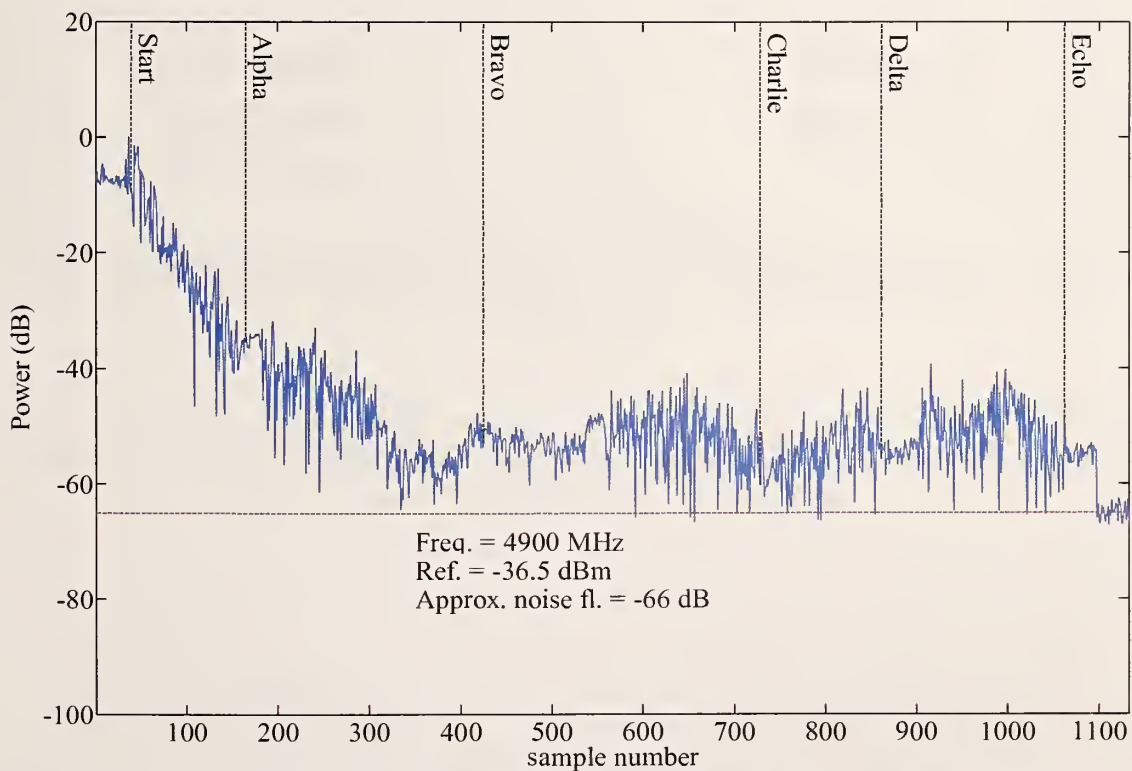


Figure 243. SUNCOR oil refinery road drive at 4900.0 MHz; receiver at north site.

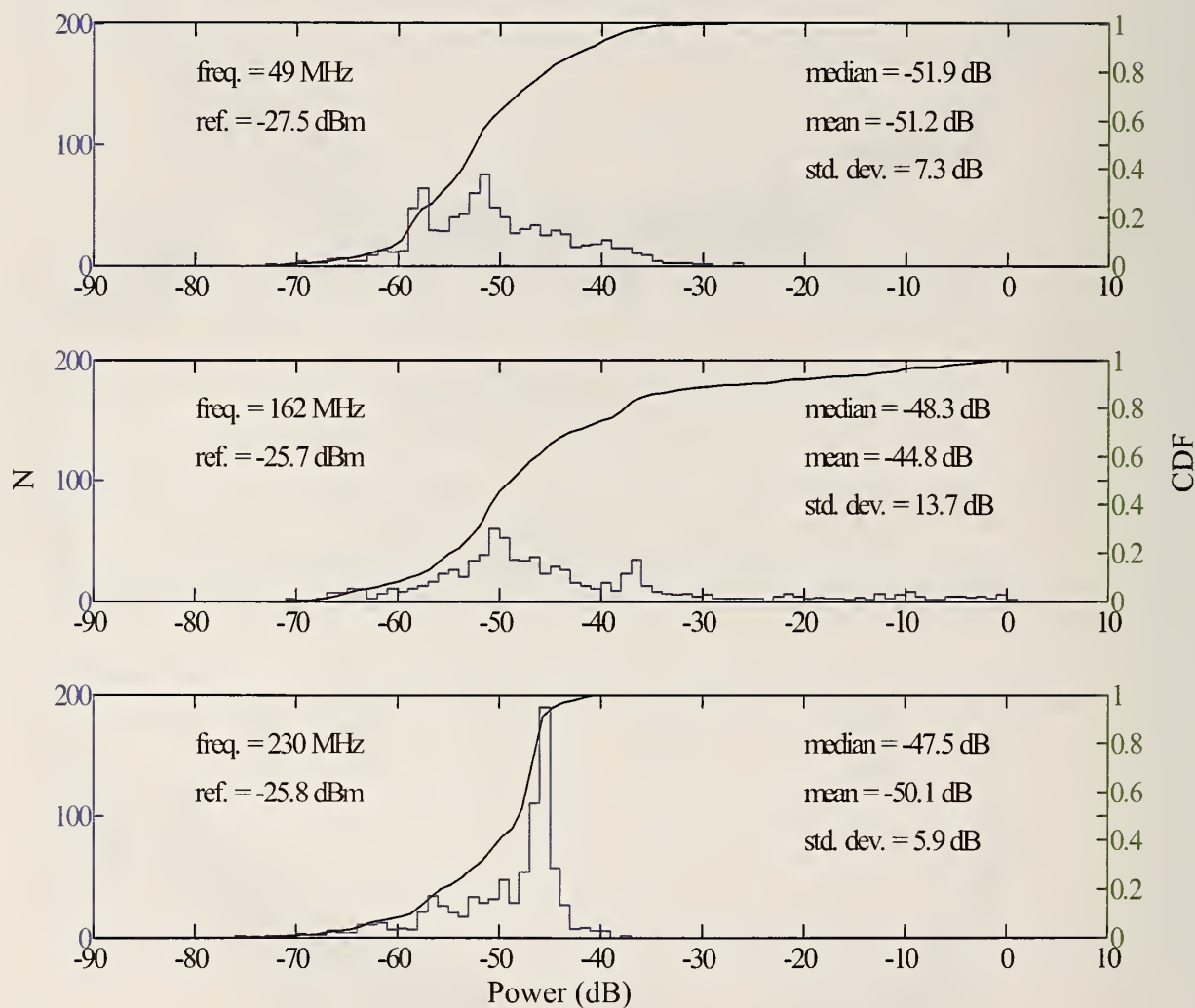


Figure 244. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 49.85, 162.075, and 230.0 MHz.

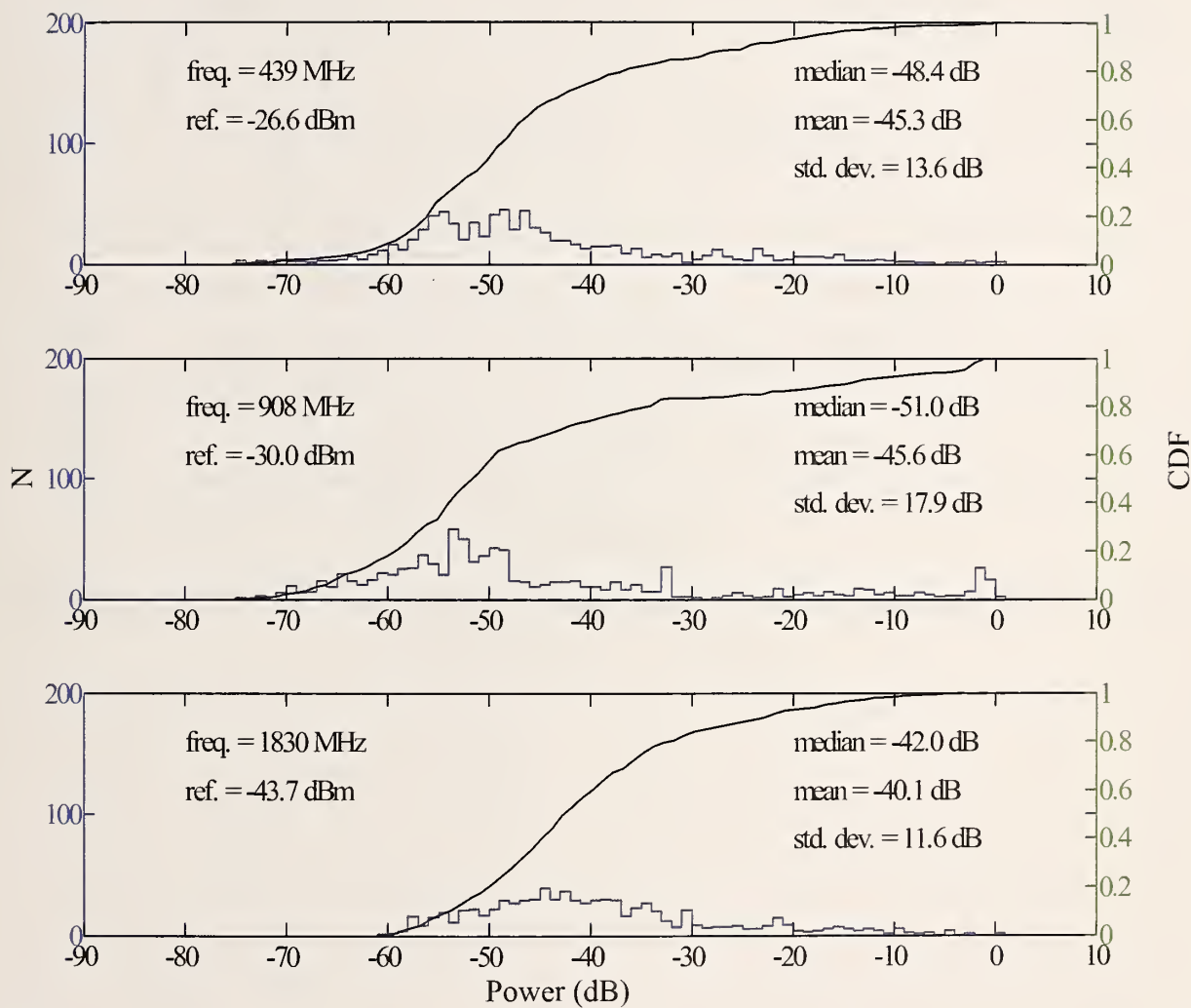


Figure 245. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 439.25, 908.0, and 1830.1 MHz.



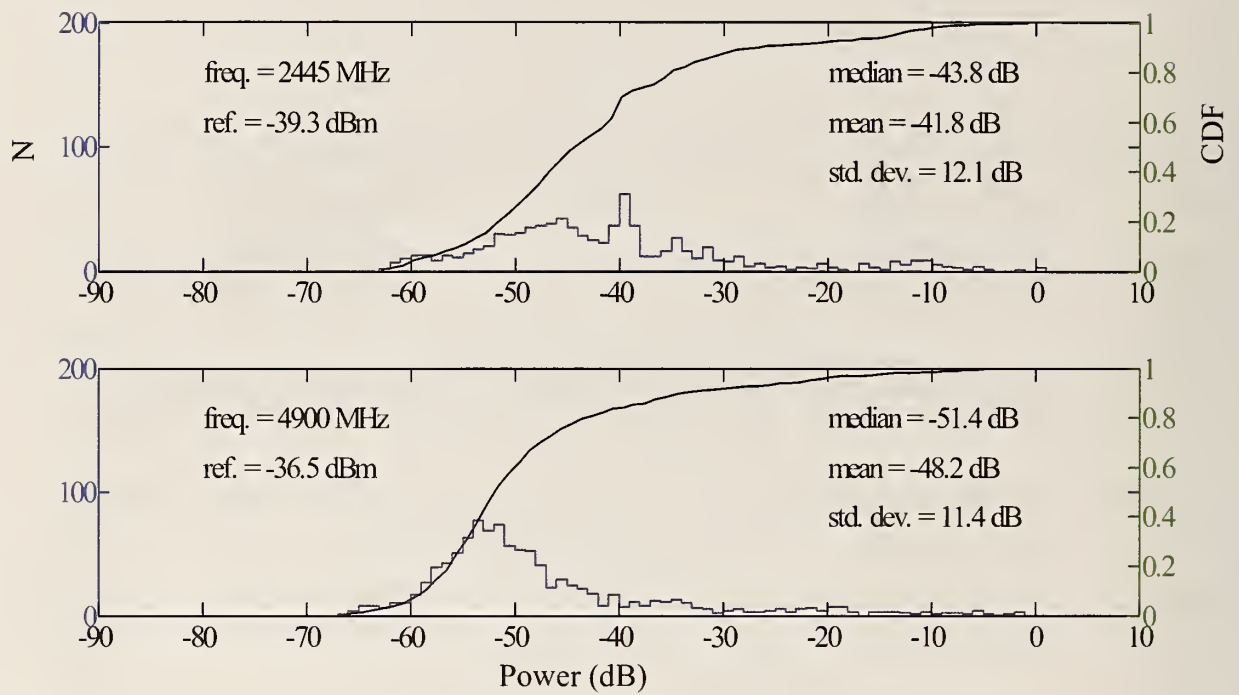


Figure 246. SUNCOR oil refinery statistics, histograms, and empirical CDF for walk-through data at 2445.0 and 4900.0 MHz.

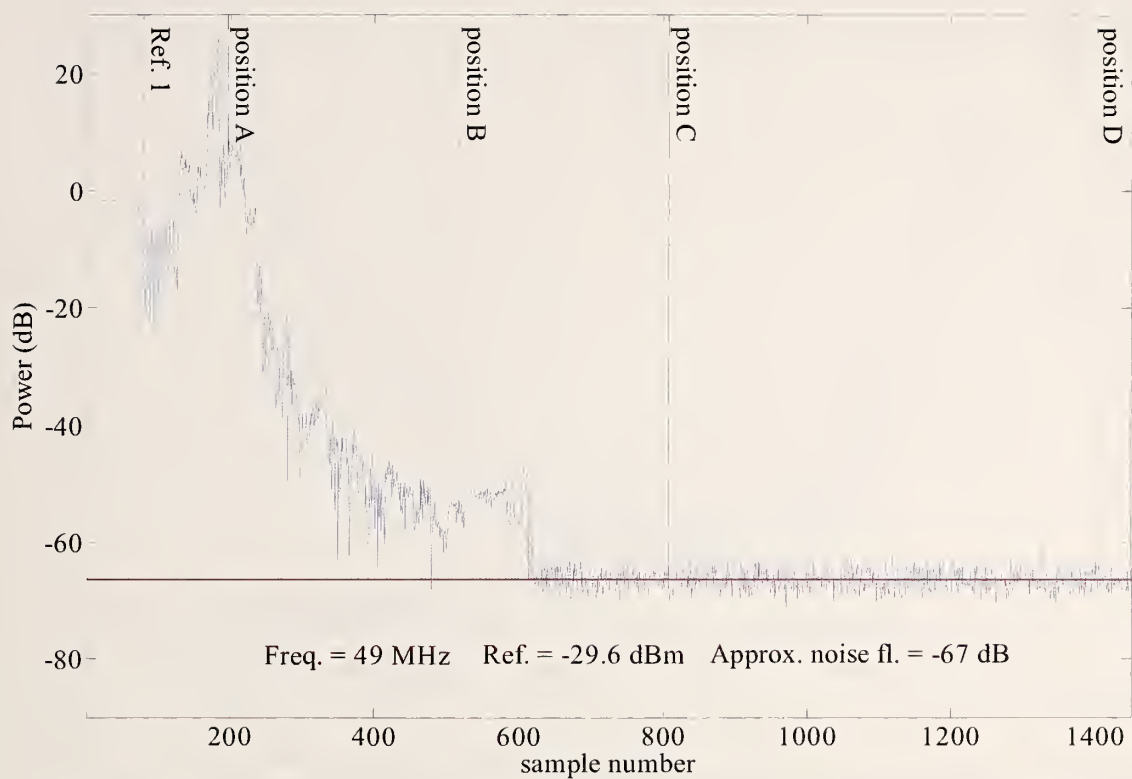


Figure 247. NIST Boulder laboratory walk-through at 49.8 MHz; receiver at wing 4 site.

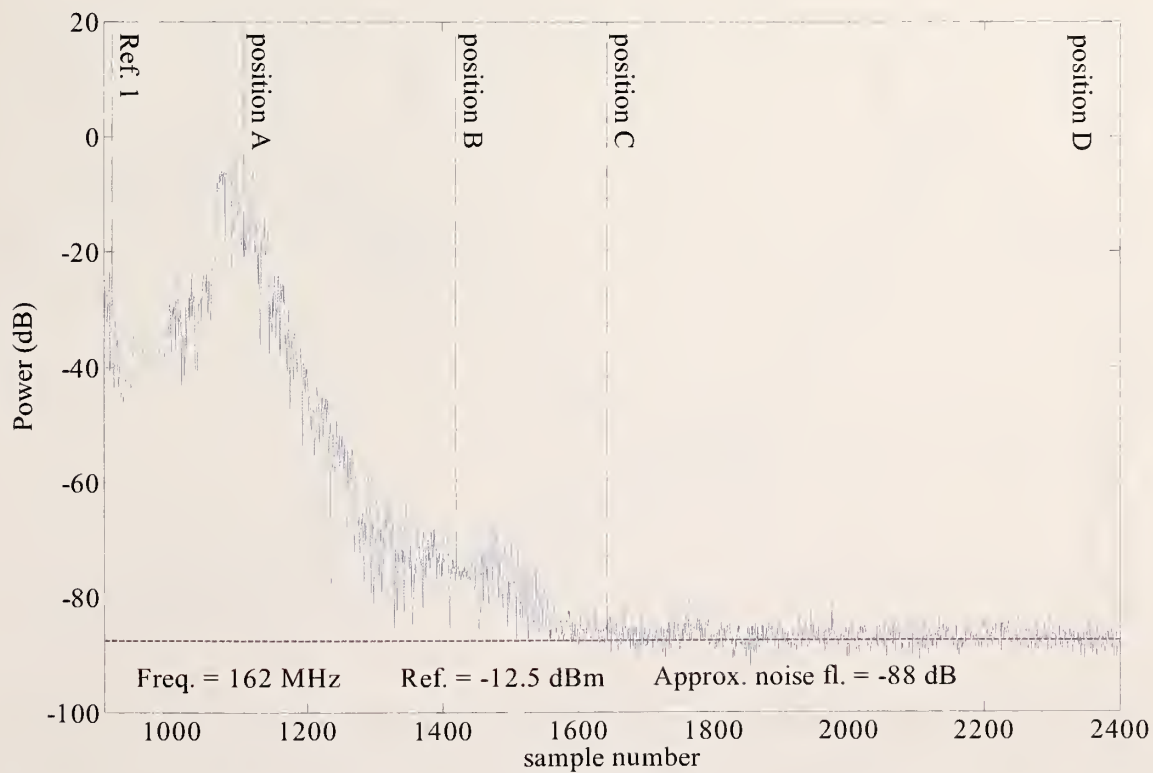


Figure 248. NIST Boulder laboratory walk-through at 162.075 MHz; receiver at wing 4 site.

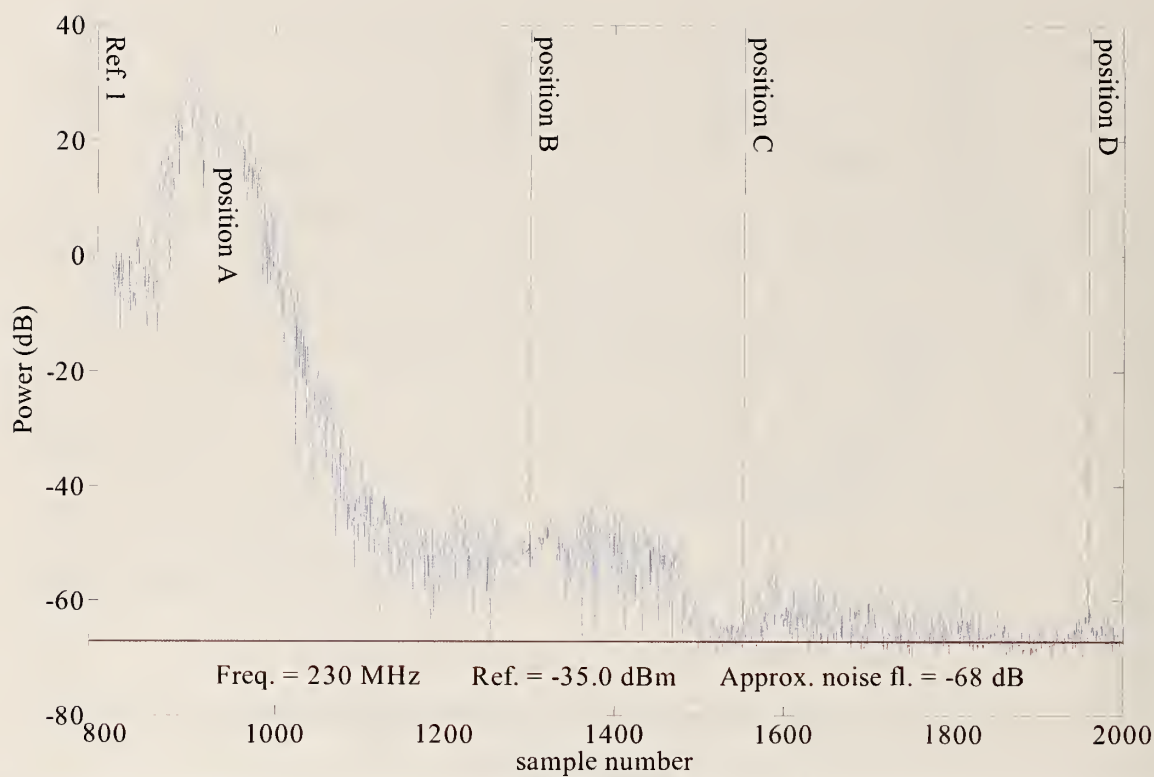


Figure 249. NIST Boulder laboratory walk-through at 230.0 MHz; receiver at wing 4 site.

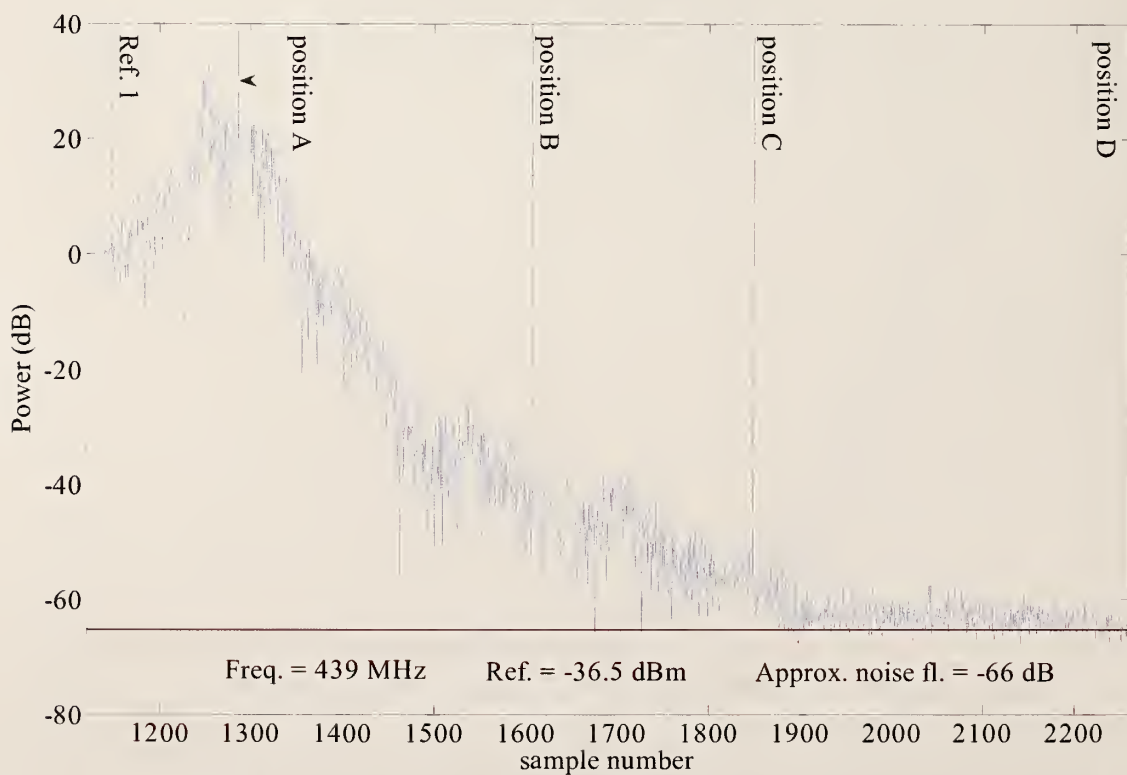


Figure 250. NIST Boulder laboratory walk-through at 439.25 MHz; receiver at wing 4 site.

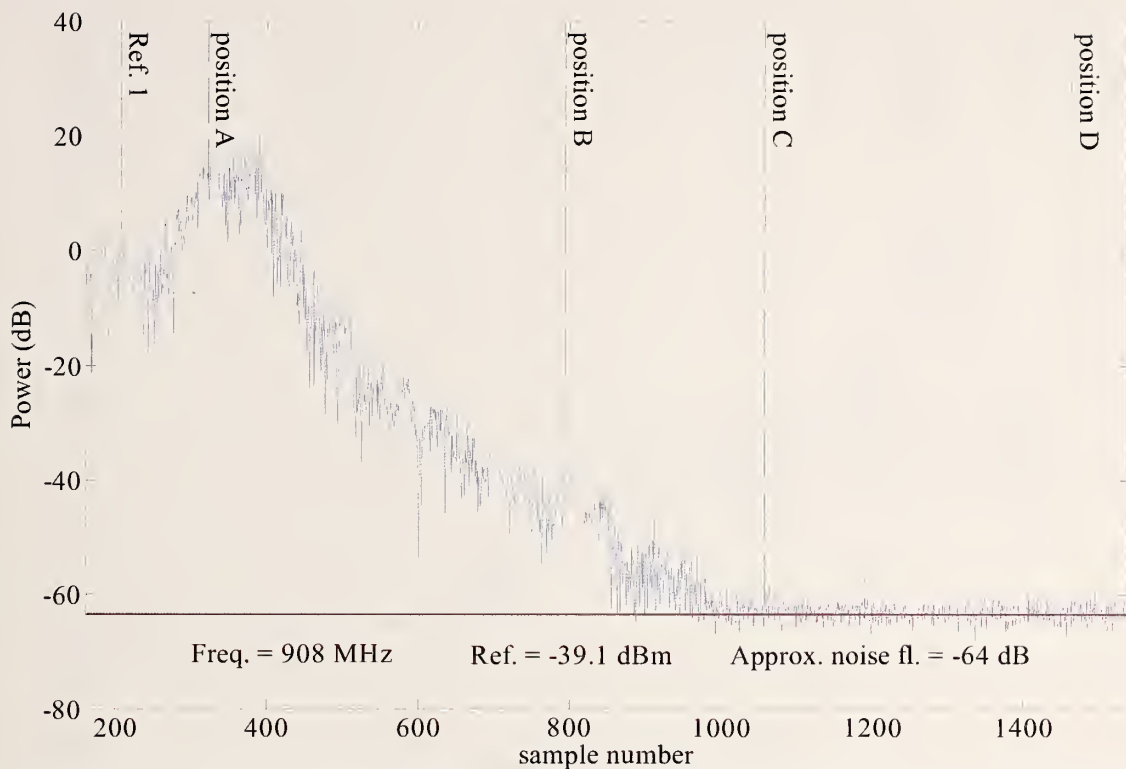


Figure 251. NIST Boulder laboratory walk-through at 908.0 MHz; receiver at wing 4 site.

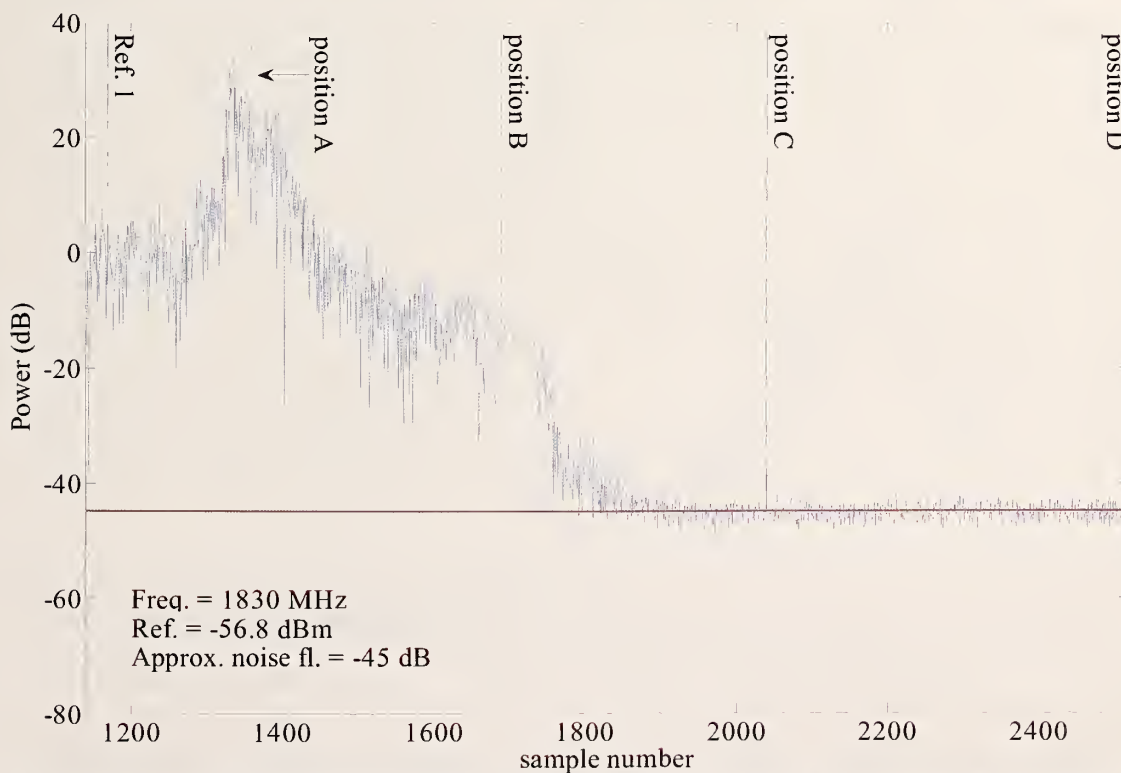


Figure 252. NIST Boulder laboratory walk-through at 1830.0 MHz; receiver at wing 4 site.



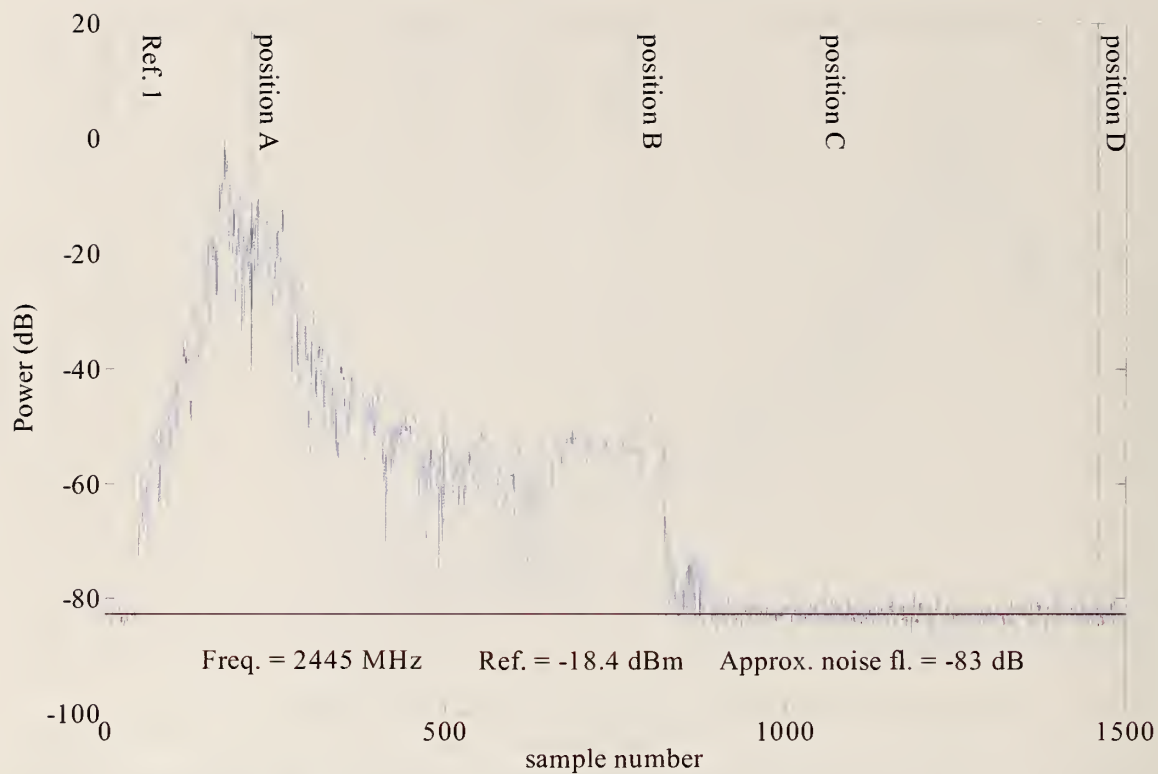


Figure 253. NIST Boulder laboratory walk-through at 2445.0 MHz; receiver at wing 4 site.

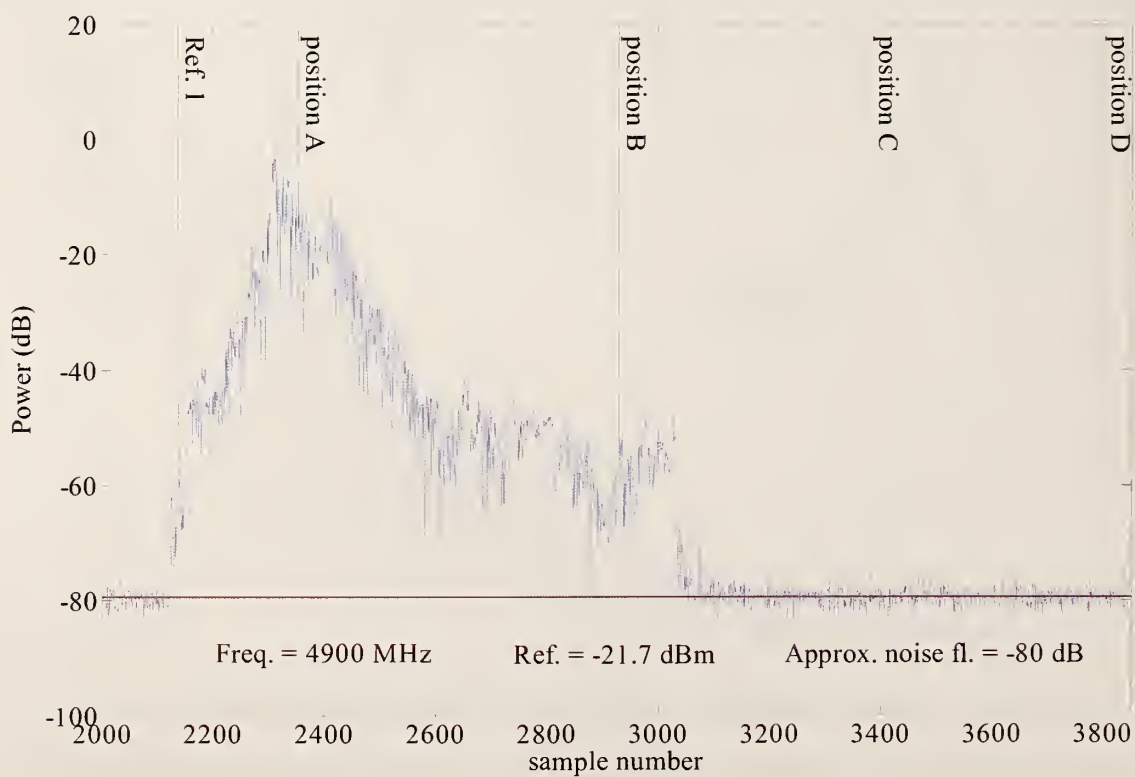


Figure 254. NIST Boulder laboratory walk-through at 4900.0 MHz; receiver at wing 4 site.

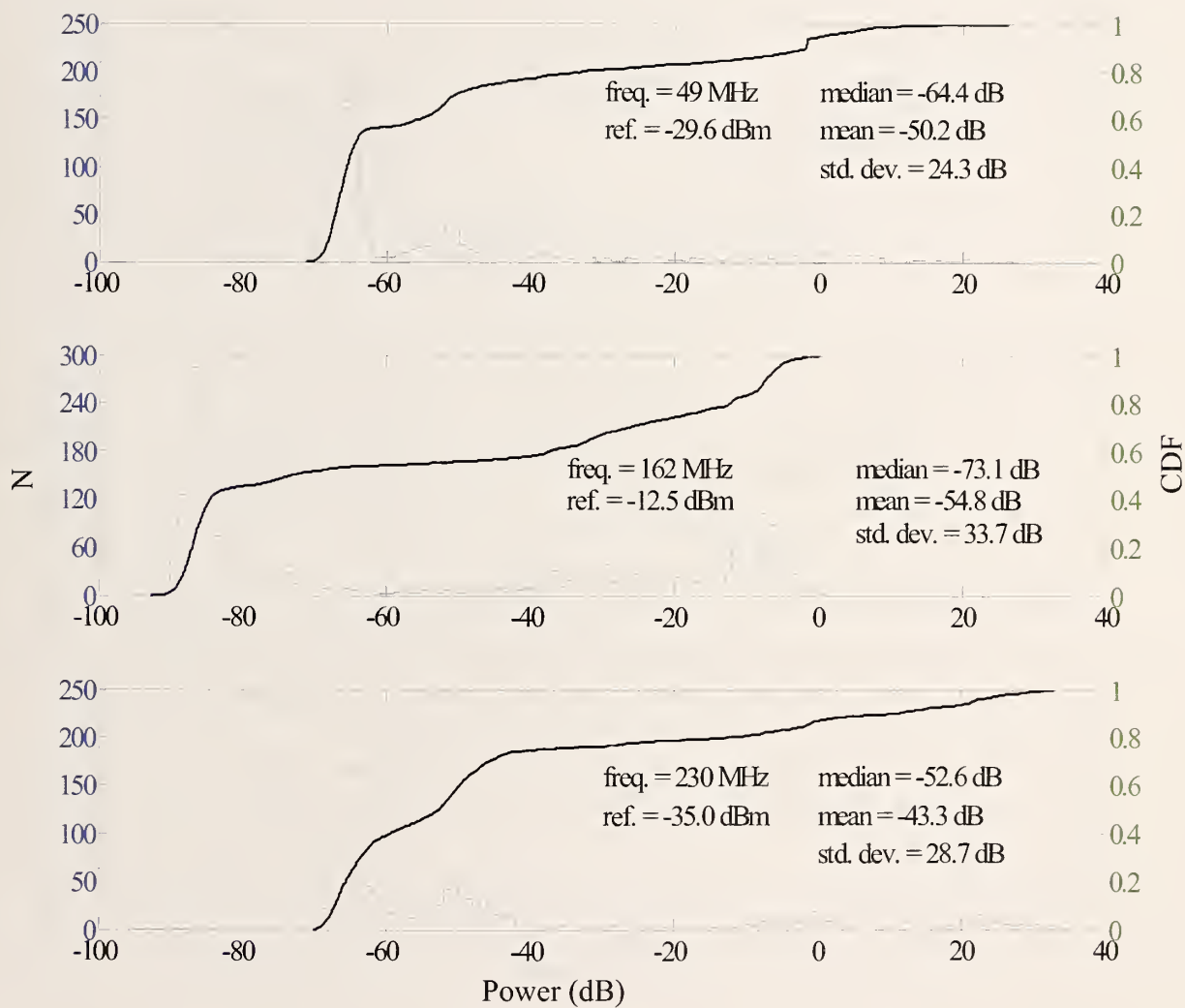


Figure 255. NIST Boulder laboratory statistics, histograms, and empirical CDF for walk-through data at 49.8, 162.075, and 230.0 MHz; receiver at wing 4 site.

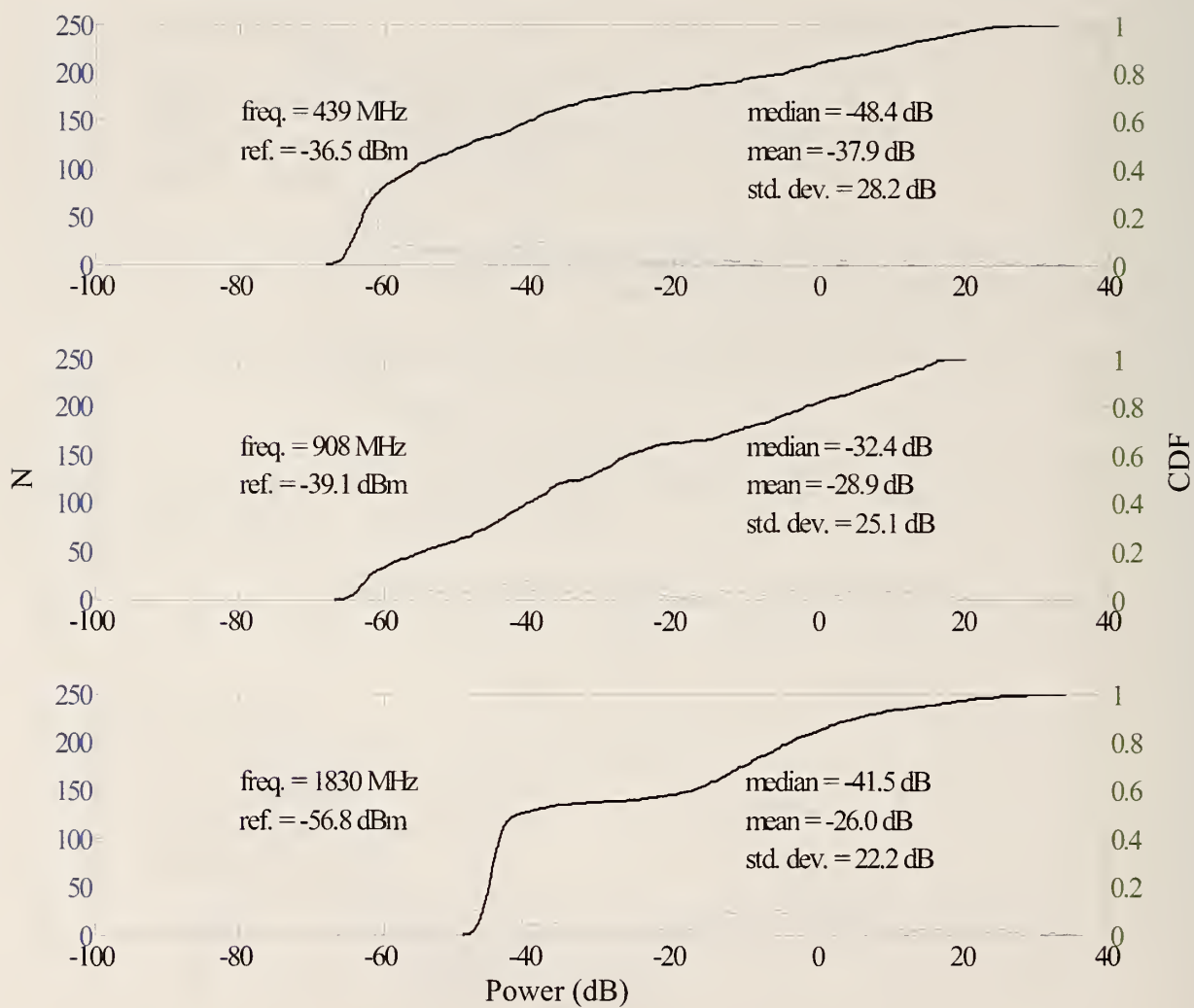


Figure 256. NIST Boulder laboratory statistics, histograms, and empirical CDF for walk-through data at 439.25, 908.0, and 1830.0 MHz; receiver at wing 4 site.

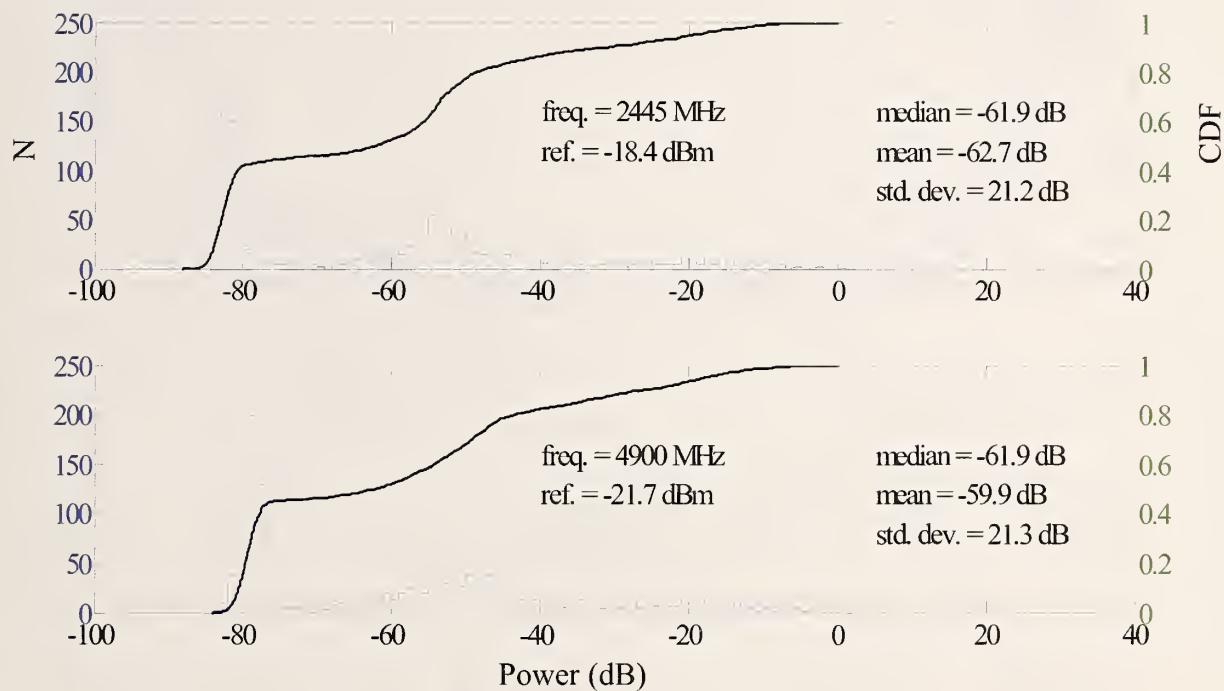


Figure 257. NIST Boulder laboratory statistics, histograms, and empirical CDF for walk-through data at 2445.0 and 4900.0 MHz; receiver at wing 4 site.



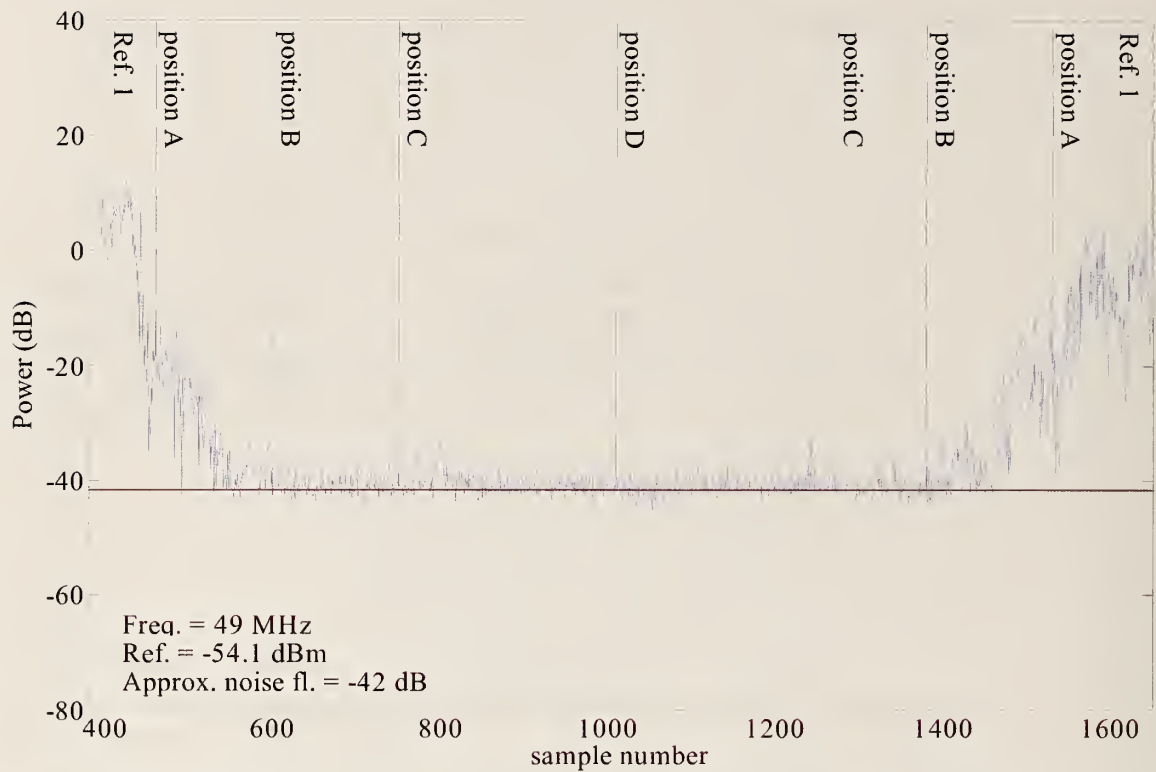


Figure 258. NIST Boulder laboratory walk-through at 49.8 MHz; receiver at wing 6 site.

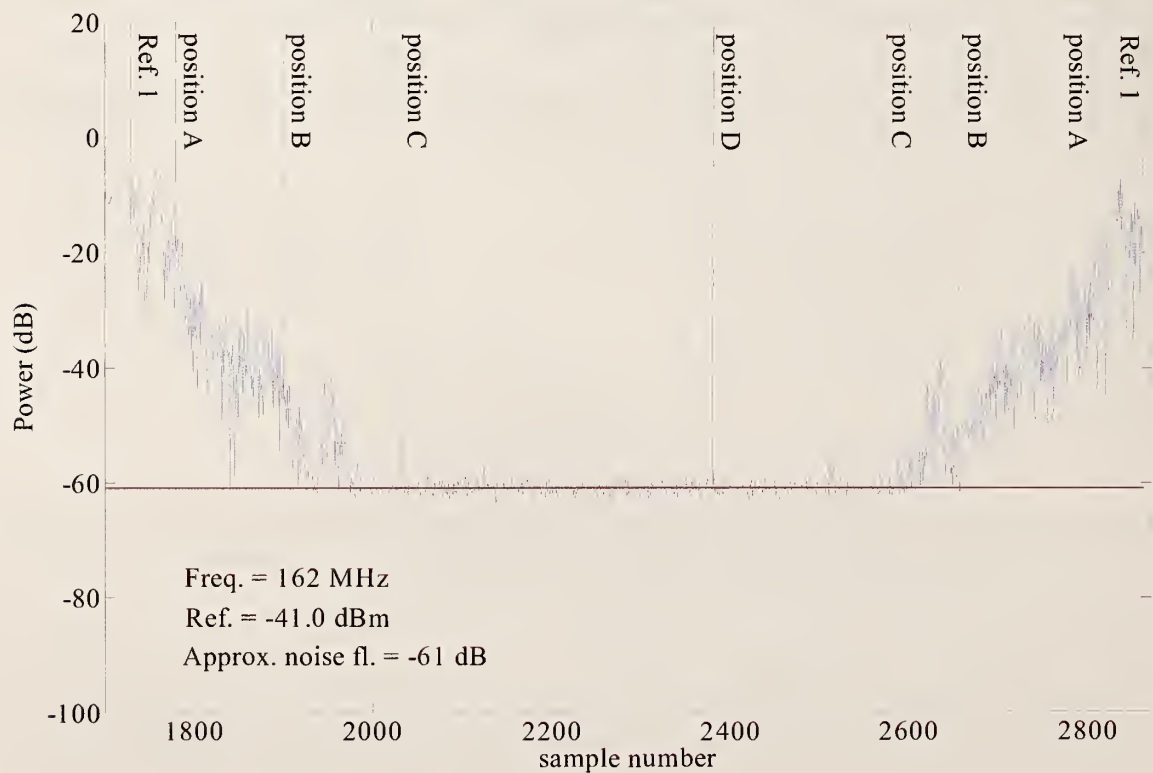


Figure 259. NIST Boulder laboratory walk-through at 162.075 MHz; receiver at wing 6 site.

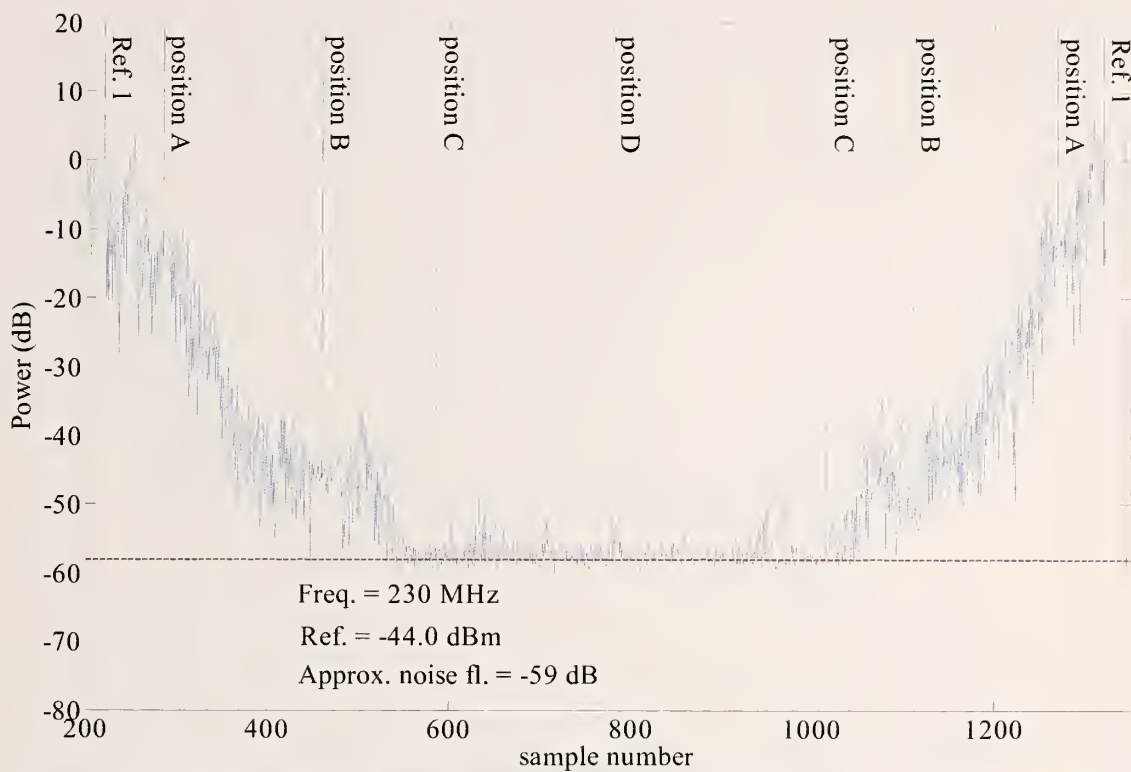


Figure 260. NIST Boulder laboratory walk-through at 230.0 MHz; receiver at wing 6 site.

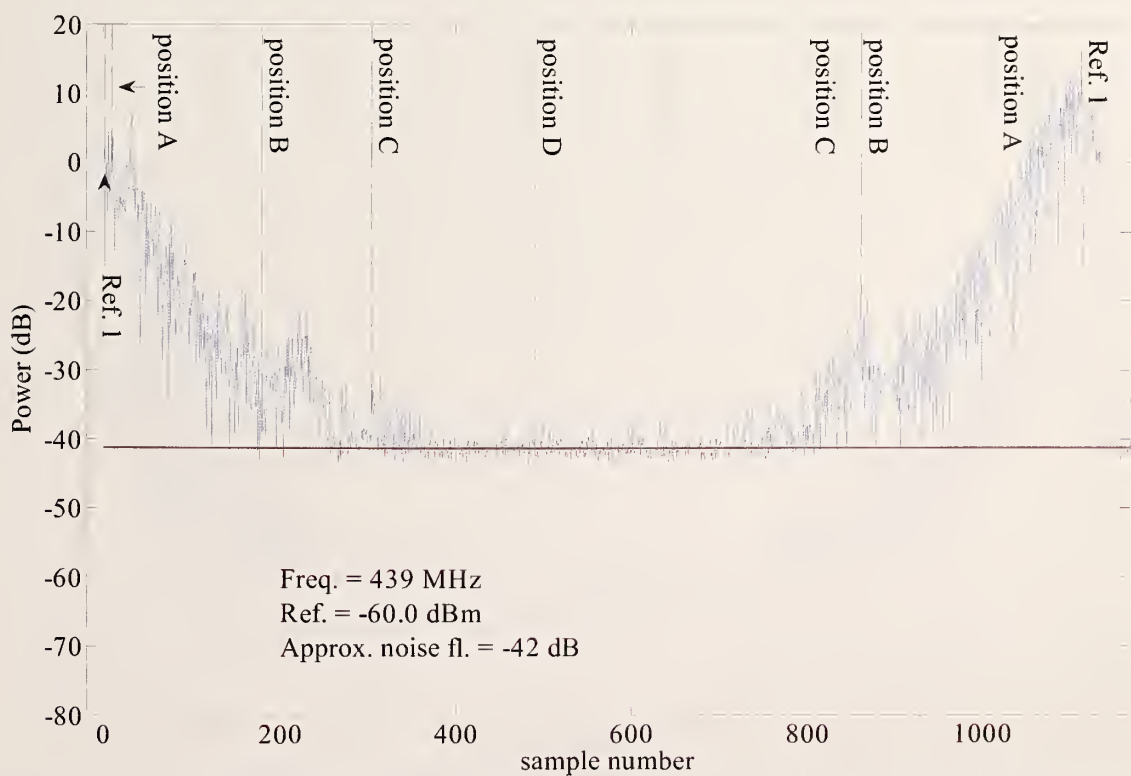


Figure 261. NIST Boulder laboratory walk-through at 439.25 MHz; receiver at wing 6 site.

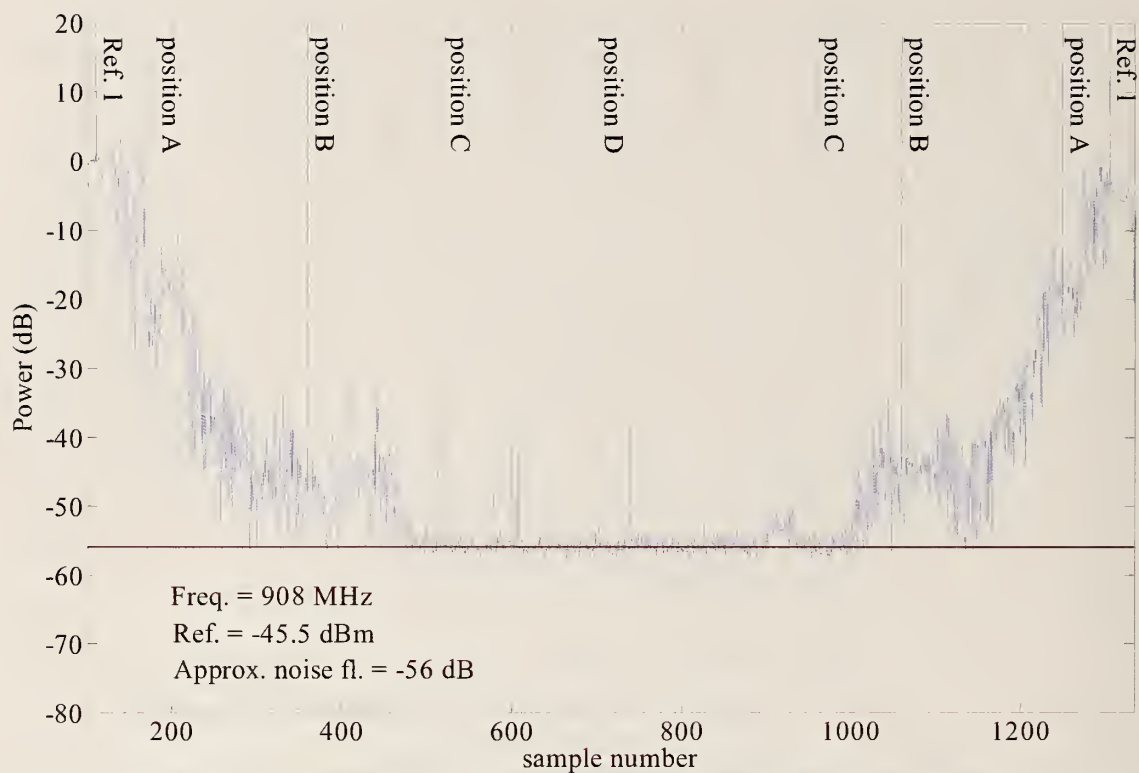


Figure 262. NIST Boulder laboratory walk-through at 908.0 MHz; receiver at wing 6 site.

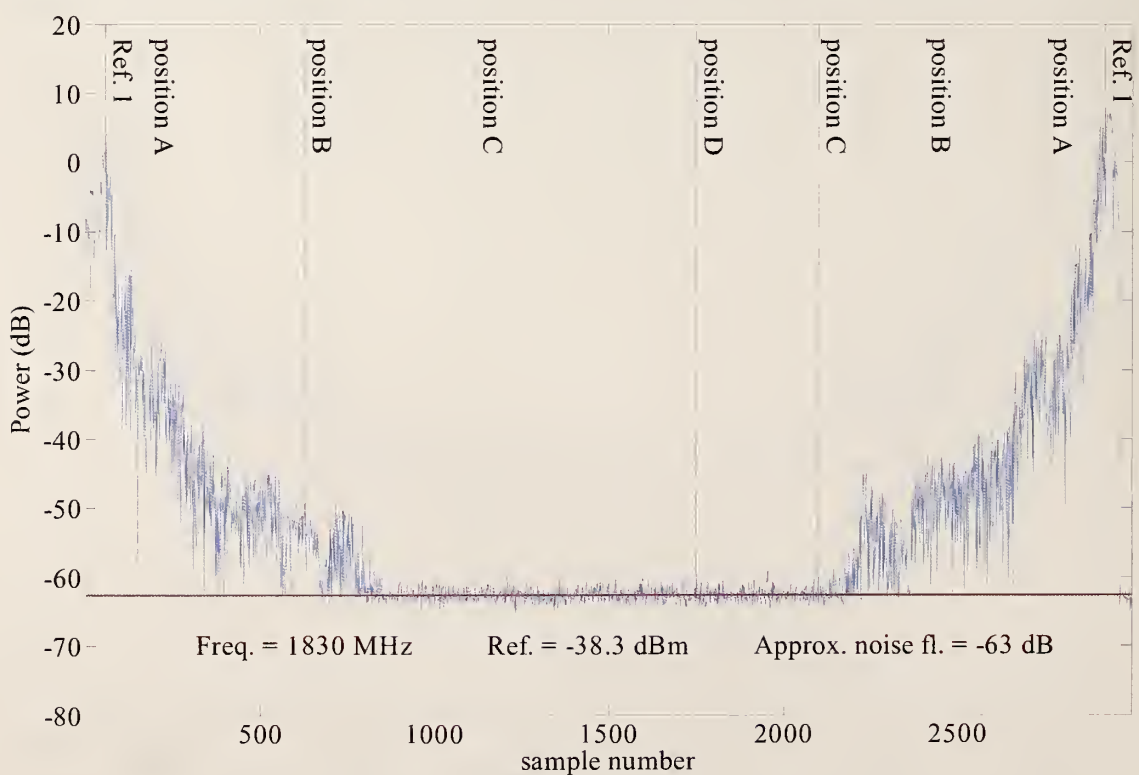


Figure 263. NIST Boulder laboratory walk-through at 1830.0 MHz; receiver at wing 6 site.

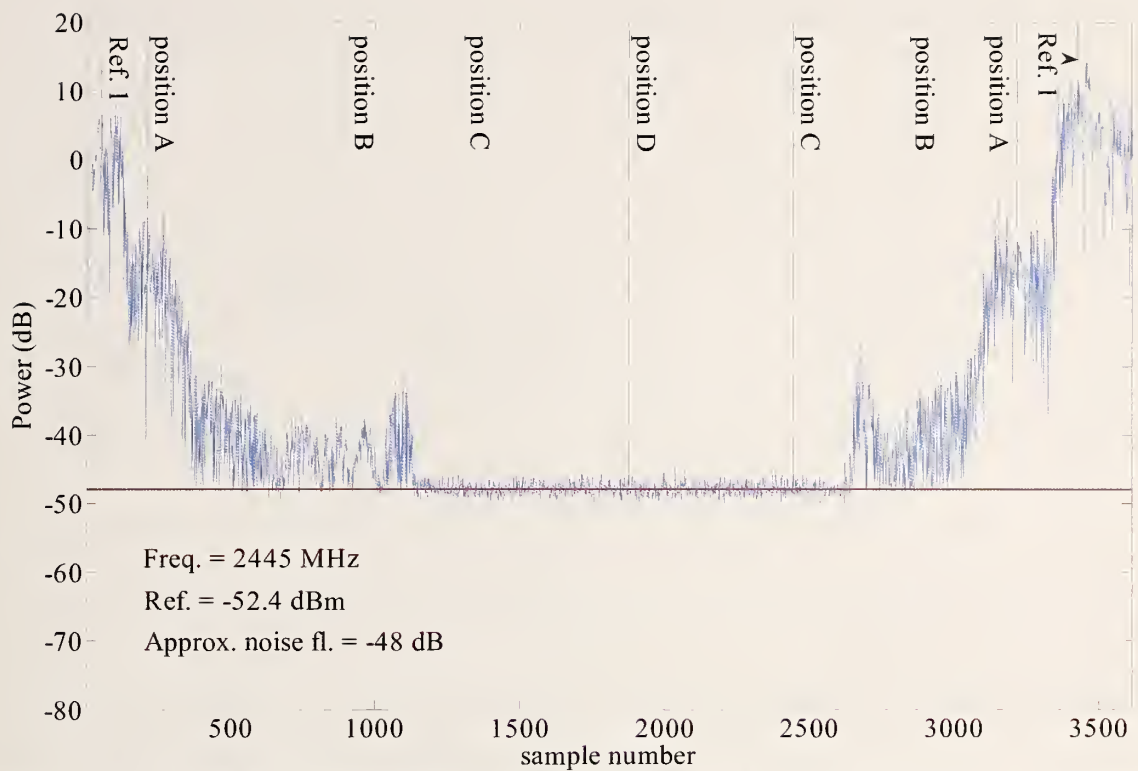


Figure 264. NIST Boulder laboratory walk-through at 2445.0 MHz; receiver at wing 6 site.

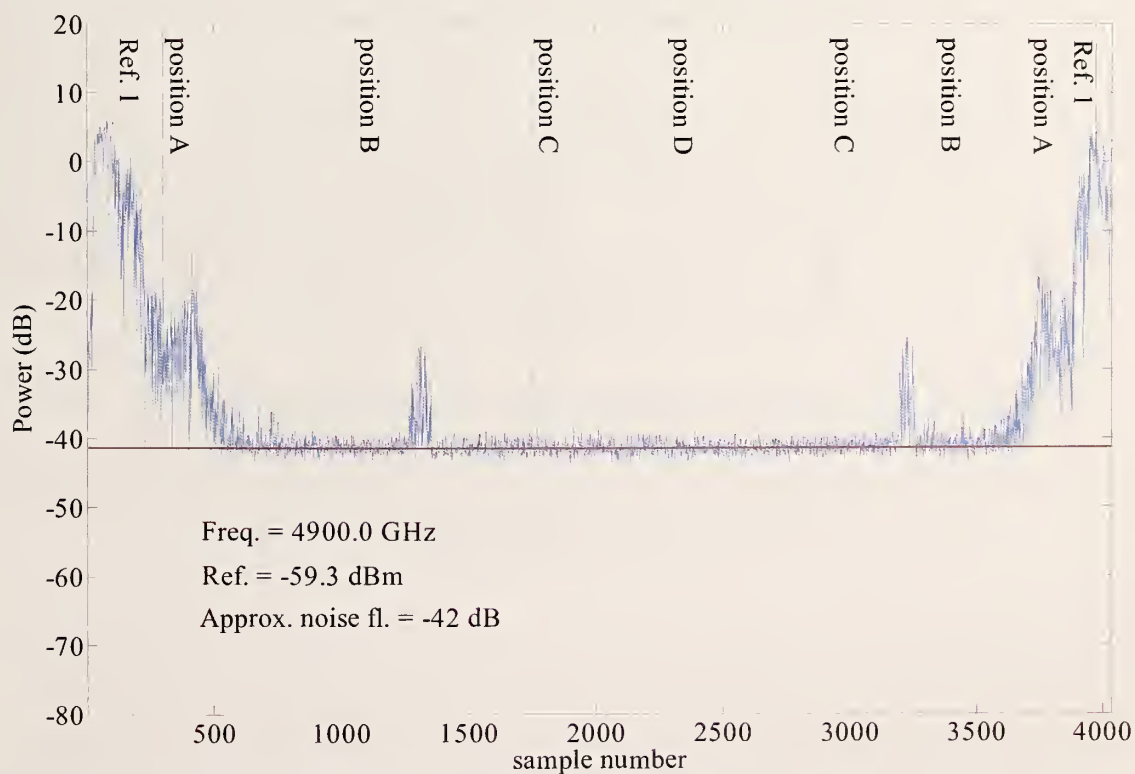


Figure 265. NIST Boulder laboratory walk-through at 4900.0 MHz; receiver at wing 6 site.



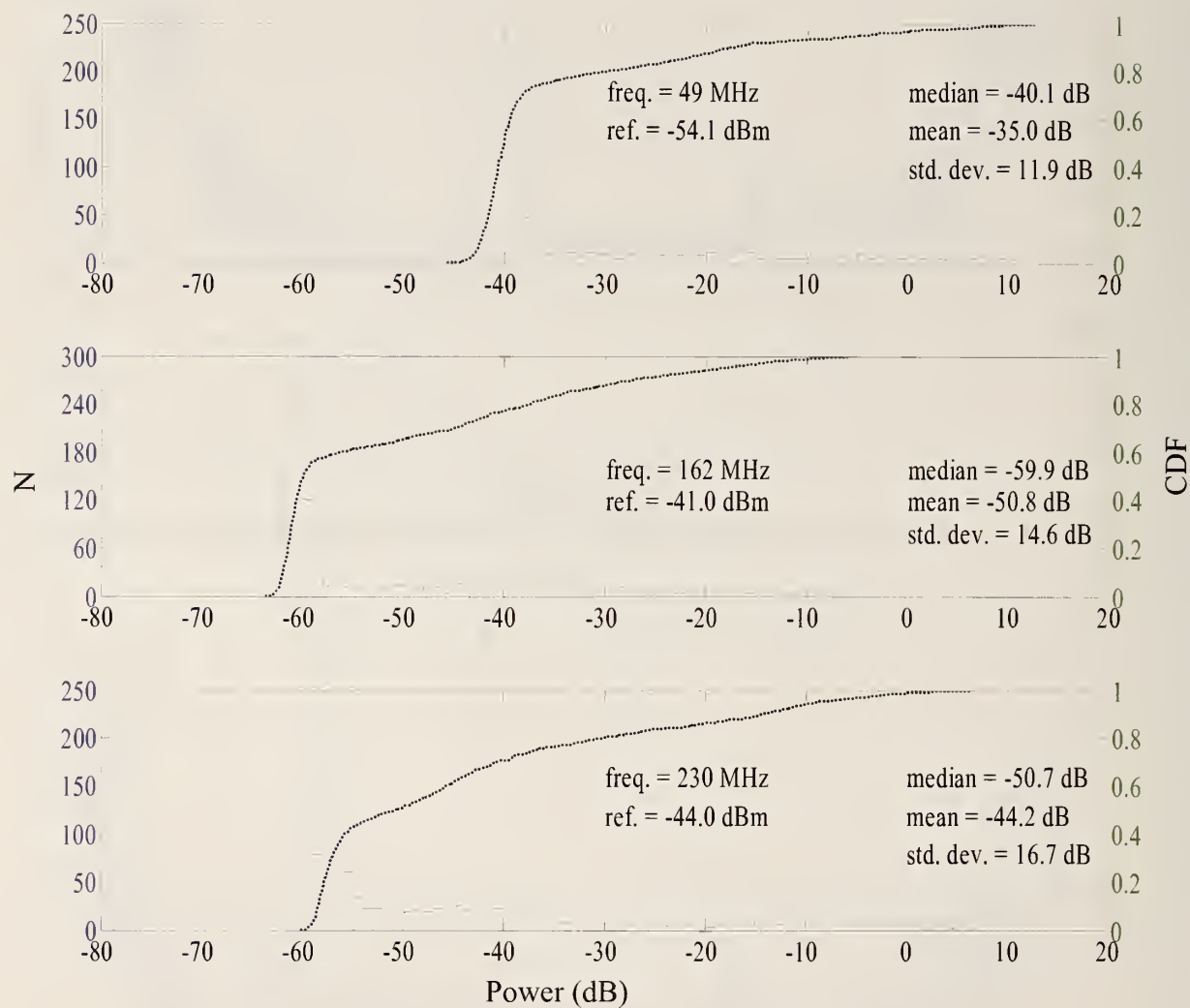


Figure 266. NIST Boulder laboratory statistics, histograms, and empirical CDF for walk-through data at 49.8, 162.075, and 230.0 MHz, receiver at wing 6 site.

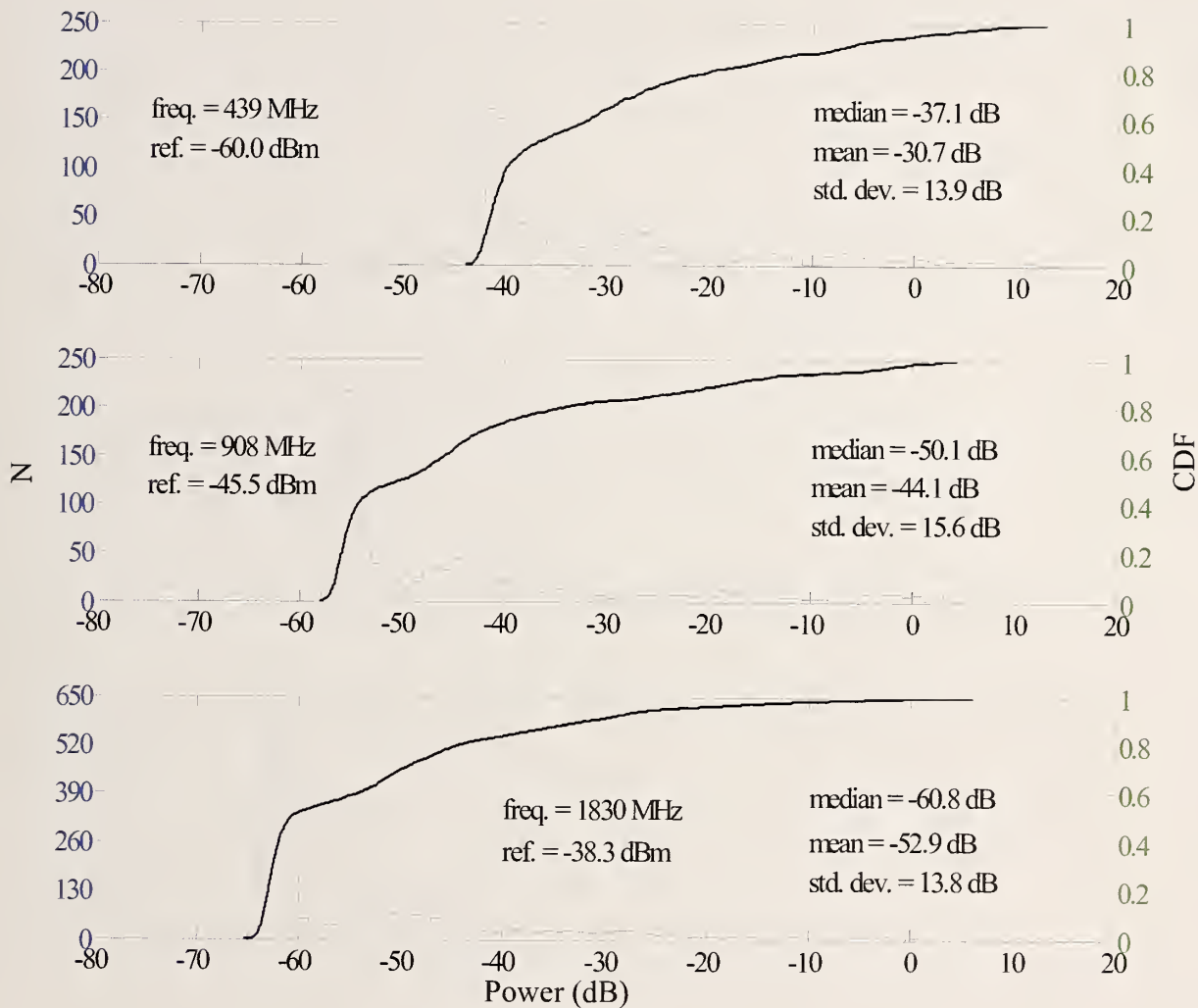


Figure 267. NIST Boulder laboratory statistics, histograms, and empirical CDF for walk-through data at 439.25, 908.0, and 1830.0 MHz; receiver at wing 6 site.

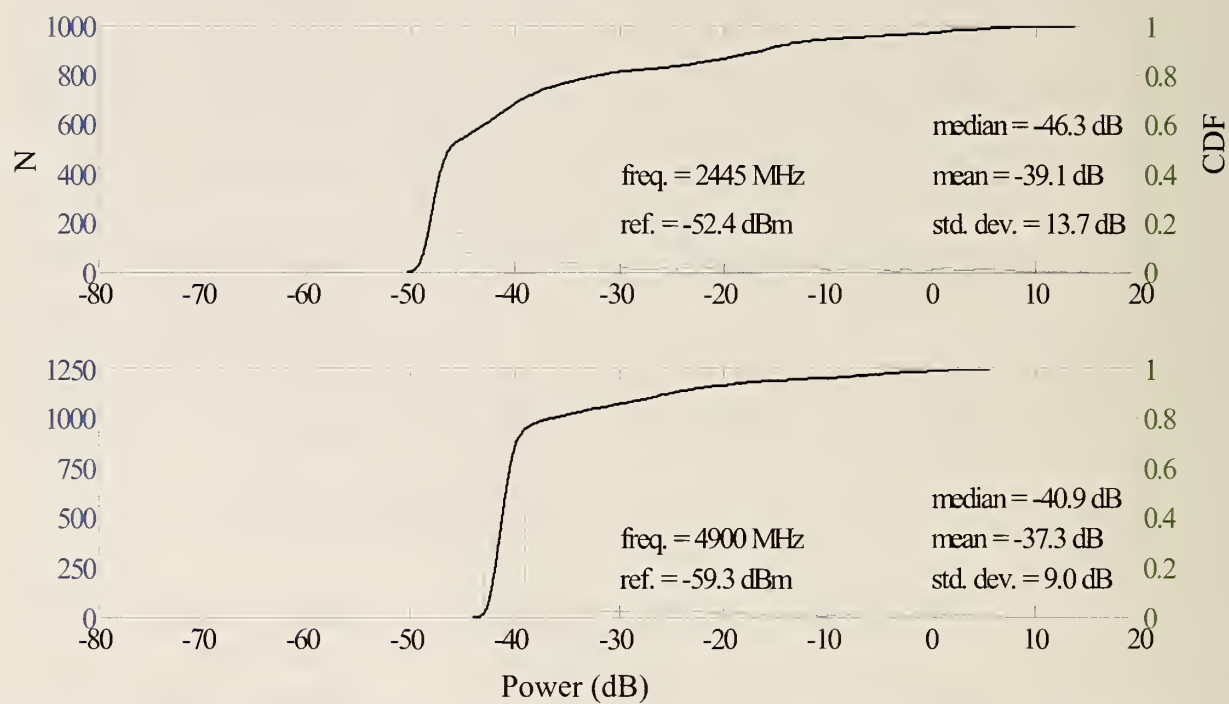


Figure 268. NIST Boulder laboratory statistics, histograms, and empirical CDF for walk-through data at 2445.0 and 4900.0 MHz; receiver at wing 6 site.

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